Electromagnetic Transient and Electromechanical Transient Stability Hybrid
Simulation: Design, Development and its Applications

by

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ABSTRACT

Two significant trends of recent power system evolution are: (1) increasing installation of dynamic loads and distributed generation resources in distribution systems; (2) large-scale renewable energy integration at the transmission system level. A majority of these devices interface with power systems through power electronic converters. However, existing transient stability (TS) simulators are inadequate to represent the dynamic behavior of these devices accurately. On the other hand, simulating a large system using an electromagnetic transient (EMT) simulator is computationally impractical. EMT-TS hybrid simulation approach is an alternative to address these challenges. Furthermore, to thoroughly analyze the increased interactions among the transmission and distribution systems, an integrated modeling and simulation approach is essential.

The thesis is divided into three parts. The first part focuses on an improved hybrid simulation approach and software development. Compared to the previous work, the proposed approach has three salient features: three-sequence TS simulation algorithm, three-phase/three-sequence network equivalencing and flexible switching of the serial and parallel interaction protocols.

The second part of the thesis concentrates on the applications of the hybrid simulation tool. The developed platform is first applied to conduct a detailed fault-induced delayed voltage recovery (FIDVR) study on the Western Electricity Coordinating Council (WECC) system. This study uncovers that after a normally cleared single line to ground fault at the transmission system could cause air conditioner motors to stall in the distribution systems,
and the motor stalling could further propagate to an unfaulted phase under certain conditions. The developed tool is also applied to simulate power systems interfaced with HVDC systems, including classical HVDC and the new generation voltage source converter (VSC)-HVDC system.

The third part centers on the development of integrated transmission and distribution system simulation and an advanced hybrid simulation algorithm with a capability of switching from hybrid simulation mode to TS simulation. Firstly, a modeling framework suitable for integrated transmission and distribution systems is proposed. Secondly, a power flow algorithm and a diakoptics based dynamic simulation algorithm for the integrated transmission and distribution system are developed. Lastly, the EMT-TS hybrid simulation algorithm is combined with the diakoptics based dynamic simulation algorithm to realize flexible simulation mode switching to increase the simulation efficiency.
DEDICATION

To my father Yaquan Huang, my mother Riqing Jiang, my younger brother Jianhua Huang and my wife Ximing Lin for their love and endless support.
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NOMENCLATURE

$A_k$  
The incidence matrix correlating the buses in subsystem $k$ with the link branches

$\bar{A}_k$  
The incidence matrix correlating the boundary buses in subsystem $k$ with the link branches

A/C  
Air conditioner

API  
Application programming interfaces

$B$  
A set of boundary buses

BES  
Bulk electric system

CFA  
Curve fitting analysis

CIGRE  
Conseil International des Grands Réseaux Électriques or International Council on Large Electric Systems

CLM  
Composite load model

$D_{avg}$  
The average simulation difference between the hybrid simulation and the full-blown EMT simulation

$D_{max}$  
The maximum simulation difference between the hybrid simulation and the full-blown EMT simulation

DFS  
Depth first search algorithm

DG  
Distributed generation

DOE  
U.S. Department of Energy

DS  
Dynamic simulation

$E$  
A set of the buses in the external system

EMT  
Electromagnetic transient

FACTS  
Flexible alternating current transmission system

FDNE  
Frequency dependent network equivalent

FFT  
Fast Fourier transform

FIDVR  
Fault induced delayed voltage recovery

GUI  
Graph user interface
HVDC  High voltage direct current
IPC  Inter-process communication

$I$  A vector of bus current injections
$I^{(s)}$  A vector of bus sequence current injections
$I_{dc}$  Dc current of the VSC-HVDC system

$I^{120}_{EMT}$  A vector of three-sequence current injections at boundary buses for representing the detailed system in the external system
$I^{(s)}_{EMT(t)}$  A vector of a sequence current injections at boundary buses for representing the detailed system in the external system at time $t$

$I_{ext}^{(0)}$  A vector of zero-sequence bus current injections in the external system
$I_{ext}^{(2)}$  A vector of negative-sequence bus current injections in the external system

$I_{l,j}^{(1)}$  The positive sequence current flowing through the branch connecting buses $i$ and $j$
$I_{l,j}^{(2)}$  The negative sequence current flowing through the branch connecting buses $i$ and $j$

$I_{inj,i}^{(2)}$  The negative sequence current injection at the bus $i$ from a distribution system to the transmission system
$I_{inj,i}^{(0)}$  The zero sequence current injection at the bus $i$ from a distribution system to the transmission system

$I_{gen}^{(1)}$  The current source of a positive sequence Norton equivalent of a generator
$I_{abc}^{gen}$  The current source of a three-phase Norton equivalent of a generator

$I_k$  The bus current injection vector of subsystem $k$

$I_{Link}$  A vector of the currents flowing through the link branches

$I_{abc}^{Ni}$  Norton equivalent current source of boundary bus $i$ in three-sequence

$I_{120}^{Ni}$  Norton equivalent current source of boundary bus $i$ in three-phase

$I_{\varphi}^{Ni}$  Norton equivalent current source of phase $\varphi$ of bus $i$

$LoadPQ_i^{(1)}$  The positive-sequence equivalent load of distribution system $i$

$M$  The number of boundary buses

MATE  Multi-area Thévenin equivalent
$N$ \hspace{1cm} The total number of outputs for a monitoring variable during hybrid simulation

$N_{\text{dist},i}^{\text{new}}$ \hspace{1cm} The new bus number of the distribution bus $i$ in an integrated transmission and distribution system

$N_{\text{dist},i}^{\text{old}}$ \hspace{1cm} The original bus number of the distribution bus $i$ in a distribution system

$N_{\text{tran},i}$ \hspace{1cm} The bus number of a transmission bus to which in the associated distribution system of distribution bus $i$ connects to

NEMA \hspace{1cm} The National Electrical Manufacturers Association

NERC \hspace{1cm} North American Electric Reliability Corporation

OOP \hspace{1cm} Object-oriented programming

$p_e^{(2)}$ \hspace{1cm} The negative sequence power of a machine modeled in three-sequence detail

$p_{\varphi, i}^{\omega}$ \hspace{1cm} The real power of the load on phase $\varphi$ of bus $i$, $\varphi \in \{A, B, C\}$

$P_{\text{Total},i}$ \hspace{1cm} The real part of the total loads of bus $i$

POW \hspace{1cm} Point-on-wave

PV \hspace{1cm} Photovoltaics

POSIX \hspace{1cm} Portable operating system interface

$R_{\text{im}(i,j)}$ \hspace{1cm} Current imbalance index for the branch connecting buses $i$ and $j$

$R_{\text{EMT}}^{120}$ \hspace{1cm} The maximum rate of change of the three-sequence current injections from the detailed system into the external system

$s$ \hspace{1cm} A sequence, and $s = 1, 2$ and $0$ represent the positive-, negative- and zero-sequence

$S$ \hspace{1cm} A three-sequence to three-phase transformation matrix

$S_{\text{SUB}}$ \hspace{1cm} A set representing the subsystems in a network

$t$ \hspace{1cm} The present time in hybrid simulation

$\Delta T$ \hspace{1cm} The transient stability simulation time step or the interaction time step

TCP/IP \hspace{1cm} Transmission control protocol/internet protocol

TCSC \hspace{1cm} Thyristor-controlled series compensator

TDDS \hspace{1cm} Integrated transmission and distribution system dynamic simulation algorithm

TDPF \hspace{1cm} Integrated transmission and distribution system power flow algorithm

$T_{\text{max}}$ \hspace{1cm} The maximum simulation time

xxi
Transient stability

Voltage source converter

A vector of sequence voltages of the boundary buses

A vector of three-sequence voltages of the boundary buses

The three-phase boundary bus voltages of bus $i$

DC voltage of a converter of VSC-HVDC system

The network solution result (bus voltages) of the subsystem $i$ without considering the effects of the connected subsystems

The equivalent source voltage of the link subsystem

The zero sequence bus voltages of the external system

The negative-sequence bus voltages of the external system

The network solution result (bus voltages) of the subsystem $i$ considering only the effects of the connected subsystems

The final network solution result of the subsystem $i$

A vector of three-phase Thévenin equivalent voltages at time $t$

Thévenin voltage source of phase $\phi$ at boundary bus $i$

The positive-sequence Thévenin voltage source of subsystem $i$ viewed from the link subsystem

The three-sequence Thévenin voltage source of subsystem $i$

The three-phase Thévenin voltage source of subsystem $i$

The positive-sequence Thévenin voltage source of subsystem $i$ viewed from the boundary buses

A vector of three-sequence voltages of the boundary buses

A vector of sequence voltages of the boundary buses

Western Electricity Coordinating Council

State variables in dynamic simulation

A sequence admittance matrix of the system

A sequence admittance matrix of the external system

The admittance of a three-phase Norton equivalent of a generator

Primitive self-admittance of boundary bus $i$ in three-sequence

Primitive self-admittance of boundary bus $i$ in three-phase
\[ y_{ik} \] Primitive mutual admittance between the boundary bus \( i \) and \( k \) in three-sequence

\[ y_{ik}^{abc} \] Primitive mutual admittance between the boundary bus \( i \) and \( k \) in three-phase

\[ y_i^\phi \] Primitive self-admittance of phase \( \phi \) of boundary bus \( i \)

\[ y_i^{\phi \phi} \] Primitive mutual-admittance between the phase \( \phi \) and \( \varphi \) of boundary bus \( i \)

\[ Y_k \] The admittance matrix of the subsystem \( k \)

\[ Y_{N}^{(s)} \] A sequence equivalent admittance matrix of the external system

\[ Y_{N}^{120} \] A three-sequence equivalent admittance matrix of the external system

\[ Y_{Nik}^{120} \] A \( 3 \times 3 \) submatrix of \( Y_{N}^{120} \), representing an entry at the \( i \)th row and \( k \)th column of \( Y_{N}^{120} \)

\[ Z_{li}^{(s)} \] A sequence self-impedance of bus \( i \) in the equivalent impedance matrix \( Z_T^{(s)} \)

\[ Z_{lk}^{(s)} \] A sequence impedance of the branch connecting the boundary bus \( i \) and \( k \)

\[ Z_{ik}^{120} \] Three-sequence impedances of the branch connecting the boundary buses \( i \) and \( k \)

\[ Z_{ik}^{abc} \] Three-phase impedance of the branch connecting the boundary buses \( i \) and \( k \)

\[ Z_{ik}^{(s)} \] A sequence mutual impedance between buses \( i \) and \( k \) in the equivalent impedance matrix \( Z_T^{(s)} \)

\[ Z_i^\phi \] Primitive self-impedance of phase \( \phi \) of boundary bus \( i \)

\[ Z_i^{\phi \varphi} \] Primitive mutual-impedance between the phase \( \phi \) and \( \varphi \) of the boundary bus \( i \).

\[ Z_T^{(s)} \] A sequence equivalent impedance matrix of the external system

\[ Z_{\text{Link}} \] The equivalent impedance matrix of the link subsystem

\[ Z_{\text{Link}}^{(0)} \] A diagonal matrix of the impedances of the link branches

\[ Z_{\text{th}, k} \] The positive sequence Thévenin impedance matrix of the subsystem \( k \) viewed from the link subsystem

\[ Z_{\text{th}, i}^{(120)} \] The three-sequence Thévenin impedance matrix of the subsystem \( i \)

\[ Z_{\text{th}, i}^{(abc)} \] The three-phase Thévenin impedance matrix of the subsystem \( i \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$Z_{thB,k}$</td>
<td>The positive sequence Thévenin impedance matrix of the subsystem $k$ viewed from the boundary bus(es)</td>
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<tr>
<td>$\phi, \varphi$</td>
<td>A phase of the three phases</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Three phase load unbalance factor</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Threshold of the maximum rate of change of the three-sequence current injections in the interaction protocol switching algorithm</td>
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CHAPTER 1
INTRODUCTION

1.1 Background

Existing power system operation and planning relies heavily on power system dynamic simulation to investigate the dynamic performance and transient stability of power systems. One significant recent trend in power systems is increasing number of power electronic devices interfaced with the power systems via converters. There is also an increasing installation of non-linear dynamic loads in distribution systems [2]. The dynamic behavior of power systems is increasingly influenced by these devices. Conventionally, the positive sequence based transient stability (TS) simulation [1] has been used for these system simulation tasks. TS simulation is based on a three-phase balanced assumption and it employs a single-phase, phasor modeling approach. This modeling assumption coupled with relatively large integration time step makes TS simulation inherently inadequate of modeling the fast switching and non-linear dynamics of power electronic devices, particularly under unbalanced conditions [3]-[11]. In addition, TS simulation is not designed to study a dynamic phenomenon closely related to single-phase devices in the distribution systems under unbalanced conditions. For example, the fault-induced delayed voltage recovery (FIDVR) phenomenon [2], [14]-[16], which is a focus of this research, cannot be accurately analyzed and predicted with the existing TS simulators. This is particularly true under un-symmetrical faults conditions, because the dynamic response of the single-phase residential air conditioners (A/C) cannot be adequately represented by these TS simulators [17].
On the other hand, the electro-magnetic transient (EMT) simulation [18]-[19] approach supports detailed three-phase modeling and instantaneous point-on-wave (POW) representation. Thus, EMT simulators are capable of simulating AC power systems and power electronic devices in detail. However, because of the detailed modeling and the requirement of a very small time step (in the order of micro-seconds), it is still practically inefficient to run a full EMT simulation on an actual large-scale power system, even with a state of the art computing hardware and software.

Considering the advantages and disadvantages of both types of simulation, a hybrid simulation approach, which combines both types of simulation, was proposed in [3] and has been developed over the last three decades [4]-[13]. It should be noted that TS and EMT are two different types of simulation, with considerably different modeling assumptions, solution methods and simulation time steps. It remains challenging to integrate both types of simulators in a flexible manner while achieving good accuracy and performance. Improvements and new techniques are needed in this area, including but not limited to:

1. Application to simulation of unsymmetrical faults without substantially extending the boundary and the extent of the detailed system
2. Hybrid simulation performance enhancement for realistically large systems
3. Simulation tool design and development
4. Flexible switching between hybrid simulation and TS simulation.

1.2 Fault-Induced Delayed Voltage Recovery

A fault-induced delayed voltage recovery event was first described in [14] by Gary C. Bullock. The event was first initiated by a delayed clearing of a phase-to-phase fault,
then both the 161 kV and 500 kV systems in Southwestern Tennessee experienced depressed voltage for 10-15 seconds. In [15], engineers from Southern California Edison company conducted a comprehensive study of the delayed voltage recovery at the transmission level, and provided a description of the underlying phenomenon for the first time. Their results showed that the stalling of A/C compressor motors following a fault was the root cause of FIDVR problems [15]. These delayed voltage recovery events occurred in areas with a high percentage of air conditioning loads during the summer peak air conditioning period. Similar events also occurred in Florida, and some normally cleared multiphase fault events in Southeast Florida caused a significant loss of load (200 – 825 MW) [16].

With increased penetration of low-inertia A/C loads, many electric utilities continue to experience slow voltage recovery after system faults [2]. These events, which, in most cases, only have local impacts on the portion of the power system close to the faults, still pose a risk of cascading to wider areas, especially when another unexpected fault happens while the system voltages are depressed. The U.S. DOE, NERC and WECC have been paying more attention to this issue, with a special focus on events, which result in FIDVR on the bulk electric system (BES) [2]. A fault at a high voltage level can cause voltage drop over a wide area, and that could lead to a FIDVR on the BES if the area happens to have a high concentration of A/C loads.

Increasing vulnerability to FIDVR events prompted efforts from both the industry and academia to study the FIDVR problem [2], [17], [21]-[31]. Recent research efforts
mainly focus on two areas: 1) modeling of the single-phase compressor motor of air conditioners (A/C) [17], [20]-[22] and 2) prevention and mitigation measures against FIDVR events [23]-[31]. One drawback of most of these prevention and mitigation studies is that the conventional three-phase induction motor model is used to represent the single-phase A/C compressor motors. However, the work conducted by WECC confirms that such a modeling approach is not appropriate [22]. Another issue is that none of the proposed prevention and mitigation measures have been verified under unbalanced fault conditions, primarily due to the lack of a proper simulation tool, which is capable of simulating the fast response of the single-phase A/C compressor motors as well as the slow dynamics of the system under such unbalance conditions.

1.3 Hybrid Simulation

Hybrid simulation was first proposed for analyzing fast switching dynamics of HVDC converters within power systems [18]. Since then, it has successfully drawn the attention of researchers and engineers, because it enables simulating a part of a large power system in a three-phase, device level detail without compromising or simplifying the remainder of the system. It interactively performs both EMT and TS simulations and periodically coordinates their results through interfacing variables at boundary buses.

Previous research efforts mainly focused on interfacing techniques [6], including network equivalents on both sides [4],[5],[7] interfacing protocol [8],[12],[13], iterating between EMT and TS simulations using a relaxation approach [78], and development of hybrid simulation programs [5], [9]-[12]. Several important issues related to these tech-
niques and programs need to be addressed. First, the network equivalents for both the detailed and the external systems are mainly developed based on the three-phase balanced assumption such that they are compatible with the positive sequence TS simulation. These equivalents are ideally suitable for study cases where the system is three-phase balanced. When these equivalents are applied to cases with unbalanced system conditions, the boundary has to be extended towards the external system to make sure that three phase voltages and currents are reasonably balanced at the boundary. Consequently, the extent of the detailed system is enlarged. The number of interface buses and interfacing complexity is also substantially increased. Second, either the serial or the parallel type interaction protocols are employed in most of previous hybrid simulation research. For the serial type, the EMT and TS simulators have to run sequentially during the whole simulation period, and hybrid simulation performance potential is not fully exploited. On the other end, the parallel type interaction protocol improves the simulation efficiency by enabling the EMT and TS simulators running simultaneously, however this protocol could also cause significant interfacing errors during the fault period. Thus, a new interaction protocol to achieve a better balance between the computational efficiency and accuracy is needed. Third, most of the hybrid simulation programs developed previously were designed to run all simulations on only one computer, which means the simulation can be potentially limited by the local computing resources. Last, while there are open source tools for power flow and TS simulation [32]-[33] and free tools for EMT simulation [34], there is no publically available tool
for hybrid simulation research, which, to some extent, hinders the development and application of hybrid simulation. A more detailed overview and discussion of hybrid simulation are provided in Chapter 2.

1.4 Integrated Transmission and Distribution System Simulation

The recent years has seen two significant trends in distribution systems: (1) there is an increasing penetration of distributed generation (DG) such as solar photovoltaics (PV) in distribution systems in some areas (e.g., southern California); (2) there are increased installations of dynamic loads such as air conditioners and variable frequency driven motors. The behavior of distribution systems has changed substantially. When the single-phase devices and/or DG account for a large percentage of the total peak load, their impacts on the transmission system could become significant [57]-[59]. The FIDVR problem discussed before is a good example to show the impacts.

Two types of composite load models [22], [62] have been proposed by WECC to include a distribution equivalent model and distributed generations, in order to better represent the dynamic of the distribution systems and their impacts on system dynamic behavior. Some aggregation approaches are used to build the composite load model. The basic assumption behind is that the responses of one type of devices in the same distribution system to a fault or disturbance in transmission system are more or less the same, regardless of the locations and diversity of the loads and DGs. Admittedly, the assumption is necessary to simplify the composite models, but its validity is increasingly subjected to challenges. In addition, the composite load models are basically developed for positive sequence TS simulation. It is pointed out in [22], the model is only valid for studying three-
phase faults and events, but is not applicable to simulate the effects of persistent asymmetric loads and voltages in the distribution system.

In this context, the assumption made for the distribution system modeling in conventional bulk power system dynamic simulation may no longer be valid. In order to adequately examine the impacts of more dynamic and “active” distribution systems on the transmission system and vice versa, a simulation tool which is capable of modeling and simulating transmission and distribution systems simultaneously is indispensable at both planning and operation stages [57]-[61].

Admittedly, existing EMT type simulators, such as PSCAD, can be used to conduct dynamic simulation for combined transmission and distribution systems. However, these simulators suffer from computational performance issues when applied to large-scale transmission and distribution systems. On the other hand, although there are extensive researches on TS simulation of bulk power system [1], [53], and recent years have seen increasing researches on dynamic simulation of distribution systems alone [63]-[64], research on combined transmission and distribution system modeling and simulation is comparatively limited.

A master-slave concept based power flow algorithm for integrated transmission and distribution systems is proposed in [57]-[58]. The transmission system is modeled in a positive-sequence, single-phase representation, while the distribution systems are modeled in three-phase detail. The underlying assumption is that the three-phase conditions at the interface points between transmission and distribution systems are reasonably balanced. The same modeling approach is also adopted in [59]-[60], where the integrated power flow
is realized by integrating two existing programs in a co-simulation manner. A hybrid power flow formulation unifying three-phase and single-phase representations is proposed in [78]. The boundary unbalance condition is considered and a single-port three-sequence Norton equivalent is adopted for interfacing. However, this approach is only accurate for the scenario of only one interface between the transmission system and the distribution systems, and it is not applicable to scenarios where the transmission system is interfaced with multiple distribution systems at different buses.

A three-phase phasor modeling based dynamic simulation tool has been developed in [65], where all components in both the transmission system and the distribution systems are modeled in three-phase detail. Hence, there is no interfacing issue between the transmission and the distribution systems in this approach. However, compared to modeling transmission system in positive-sequence or three-sequence, the main drawback of this approach is the increased computational burden because of increased modeling complexity. Additionally, this approach requires developing the tool entirely from scratch, while the existing, proven and well-tested positive sequence based dynamic models and algorithm cannot be properly reused. To address the computational challenges of dynamic simulation of large scale transmission and distribution systems, a domain decomposition based parallel simulation algorithm is proposed in [61] to accelerate the dynamic simulation of transmission and distribution networks. Both the transmission system and the distribution systems are represented in single-phase detail. However, modeling distribution systems in single-phase limits its applicability, since there are commonly non-perfectly transposed feeders and unbalanced loads in distribution systems.
It can be observed that power flow and dynamic simulation are dealt with separately in previous efforts. The main problem is that assumptions made for representing the integrated transmission and distribution systems for power flow are not completely consistent with those for dynamic simulation. Consequently, there are discrepancies in the models used for power flow and dynamic simulation. The power flow solution cannot be used to initialize the integrated transmission and distribution systems for dynamic simulation. To address this issue, a common modeling approach adequate for both power flow and dynamic simulation applications should be adopted.

1.5 Objective of This Research

From the background description and the literature overview above, hybrid simulation has been proven to be an effective method to simulate a large-scale power system of which a small portion of special concern can be modeled in three-phase, point-on-wave detail. This research is primarily motivated by the demand of a better simulation tool for phenomena like FIDVR in large power systems, especially under unbalanced fault conditions. For this purpose, a new hybrid simulation tool is developed, with a special focus on the following areas:

(1) Simulating unsymmetrical faults within the detailed system without extensively extending the boundary and the extent of the detailed system

(2) Improving the interaction protocol for hybrid simulation

(3) Development of a new simulation tool with the objective of making hybrid simulation flexible and accessible to other researchers
(4) Application to some critical issues that require the capability provided by the hybrid simulation, including detailed FIDVR study and dynamic simulation of power systems interfaced with power electronic converter based devices

(5) Further enhancing the simulation efficiency of hybrid simulation for 20-30 s simulations, by switching back to dynamic simulation when appropriate

In addition, to address the demand of a simulation tool for analyzing the impacts of more “active” distribution systems on bulk power systems and for transmission and distribution system integrated planning and operation, development of power flow and dynamic simulation algorithms for integrated transmission and distribution systems is an important objective in this thesis.

1.6 Organization of This Thesis

The organization of this thesis is shown in Fig. 1.1. In Chapter 1, the background of this research is described. Then, an introduction to FIDVR and an overview of EMT-TS hybrid simulation are presented. The status quo as well as the demand of combined T&D dynamic simulation is also analyzed. The objectives of this research are also outlined.

In Chapter 2, the basic concept of the EMT-TS hybrid simulation is described first. Then four critical issues concerning development of hybrid simulation, including software architecture, network equivalents of both the detailed and the external systems, interaction protocol as well as the determination of the boundary between the detailed and the external systems, are discussed.

In Chapter 3, two techniques to improve the hybrid simulation method, which are also two key features of the proposed hybrid simulation approach, are proposed. They are
The development of a hybrid simulation tool, including a three-sequence TS simulation algorithm and a socket-based communication framework for hybrid simulation, is presented in Chapter 4. Implementation details for the serial, parallel and the proposed combined interaction protocols are given. A generic framework to interface with an EMT simulator is also proposed. Interfacing with PSCAD [42] is presented as an example in detail. A hybrid simulation platform integrating the developed tool and PSCAD is built. Tests with both balanced and unbalanced fault cases confirm the effectiveness and advantages of the proposed combined interaction protocol and the three-phase/three-sequence network equivalents for hybrid simulation.
In Chapter 5, the hybrid simulation platform developed in Chapter 4 is applied to conduct a detailed simulation of the FIDVR phenomenon in a region within the WECC system. Special techniques to determine the boundary of the detailed system and initialize the detailed system with a large percentage of induction motor loads are discussed. Detailed simulation results confirm that a normally cleared single-line-to-ground fault could lead to a FIDVR event affecting all three phases. Specifically, the phenomenon of A/C motor stalling propagating to other A/C units on unfaulted phase is also uncovered for the first time. The effects of the load composition and the point-on-wave of fault inception on the occurrence and evolution of the FIDVR event are also analyzed.

In Chapter 6, the hybrid simulation tool is utilized to simulate power systems interfaced with power electronic devices. Two types of HVDC system, including the classical HVDC and the relatively new VSC-HVDC are used for testing in this research. Results show that the both the fast switching behaviors of the converters of the HVDC systems and the slow dynamics of the external system can be adequately captured by the proposed hybrid simulation. In addition, the results confirm that the hybrid simulation has a significant advantage over the full EMT simulation in terms of simulation speed.

In Chapter 7, a modeling framework for integrated transmission and distribution systems is developed, which provides a common system modeling for both power flow and dynamic simulation applications. Both power flow and dynamic simulation algorithms for integrated transmission and distribution systems are developed. In the dynamic simulation, the multi-area Thévenin equivalent approach is employed in the network solution step to
address the challenge associated with different network representations of the transmission system and the distribution systems.

In Chapter 8, an advanced hybrid simulation algorithm is developed by integrating the EMT-TS hybrid simulation developed in Chapter 4 and the multi-area dynamic simulation algorithm developed in Chapter 7. The new algorithm allows the hybrid simulation to be switched back to TS simulation when appropriate, to achieve better simulation efficiency for a relatively long (e.g., 20-30 s) simulation.

Conclusions and future research plans are presented in Chapter 9.
CHAPTER 2
HYBRID SIMULATION

2.1 Introduction to Hybrid Simulation

2.1.1 Transient Stability Simulation

In conventional positive sequence TS simulation, power systems are modeled at the fundamental frequency and with a single-phase representation of the three phases, based on the assumption of three-phase balanced and sinusoidal waveforms [1]. With these modeling considerations and a relatively large simulation time step, the TS simulation is capable of simulating the slow dynamics (mainly electromechanical transients and oscillations) of large-scale power systems at a reasonably fast simulation speed.

For simulating unbalanced faults, the symmetrical components based approach is used [1]. Any single phase device, such as single phase A/Cs, cannot be adequately modeled and simulated by TS simulation under unbalanced conditions. In addition, the quasi-steady-state (QSS) modeling approach has been used in existing TS simulators to represent the “expected” performance of power electronic converter-based devices. Therefore, their fast switching behaviors cannot be accurately represented in TS simulators.

2.1.2 Electromagnetic Transient Simulation

In contrast to TS simulation programs, each phase of the devices is modeled in detail in EMT simulation programs. In the EMT simulation, components are transformed to equivalent resistors in parallel with history current sources by using the trapezoidal integration rule, and then electromagnetic transients are solved by a nodal admittance matrix.
method proposed by H. Dommel [18]. Thus, balanced and unbalanced components can be modeled and simulated by EMT programs.

However, the common time step of EMT simulation is usually less than 100 µs, which is much smaller than that used in TS simulations (usually a quarter cycle of 60 Hz). The small time step makes EMT simulations computationally intensive. The simulation time of EMT simulations increases exponentially as the scale of the study case increases, with complexity involved in system modeling also greatly increased. Thus, the existing EMT programs are mainly used for studying cases of a relatively small scale, i.e., tens to hundreds of buses.

Two approaches have been used to increase the capability of EMT type simulations in terms of speed and modeling scale. One is parallel computing: parallel computing techniques have been applied to some commercial real time electromagnetic transient simulators [35]-[36] to increase simulation efficiency, at the cost of expensive hardware. However, it is still a challenging task to simulate a large scale power system with thousands of buses using these real time simulators. The second approach is network equivalents: system equivalencing techniques [37]-[39] are used to reduce large-scale power systems to small equivalents which can be efficiently modeled and simulated by an EMT program. There are mainly two types of equivalencing, i.e., nonlinear dynamic equivalencing and linear static equivalencing. The dynamic equivalencing techniques do not work well when applied to large scale power systems with diverse dynamic models, and they have not been widely used in the industry. To date, the static, linear equivalencing approaches, such as a
Thévenin equivalent, are commonly used. However, the dynamic responses of the external system cannot be represented by static equivalents.

2.1.3 A hybrid Simulation Approach

Hybrid simulation was first proposed for analyzing the dynamics of power systems interfaced with HVDC system by combining the TS simulation and a transient converter simulation algorithm [3]. It has been recognized that combining the EMT and the TS simulations into one simulation process provides a feasible solution to some studies where some features from both EMT and TS are required. Within the framework of hybrid simulation, a part of the study system, which requires detailed representation, is modeled and simulated in an EMT program, while the rest of the system is represented and simulated by a traditional TS program, as illustrated in Fig. 2.1. The hybrid simulation tool performs both the EMT and TS simulations and periodically coordinates their results through interfacing variables at boundary buses, which is typically accomplished using the network equivalents on both sides, as shown in Fig. 2.1 (b) and (c). The dynamic responses of single-phase devices and/or power electronic-based apparatus can be captured by the EMT program, while the advantages of the TS simulation in both speed and modeling simplicity are also fully utilized.

2.2 Key Issues Involved in EMT-TS Hybrid Simulation

Some key issues involved in the development of a hybrid simulator include [6]:

• Software architecture of a hybrid simulation program

• Network equivalents of the detailed and external system
• Interaction protocol
• Determination of the boundary between the detailed and external system

Fig. 2.1 Network splitting and equivalents for hybrid simulation: (a) the original system, (b) the detailed system and an equivalent of the external system, (c) the external system and an equivalent of the detailed system
2.2.1 Software Architecture of a Hybrid Simulation Program

Admittedly, no special attention has been paid to the software architecture of a hybrid simulator and its impact on other parts of the simulator. In fact, the architecture not only affects the selection of the communication method and interaction protocol, but also its extendibility in the future. Conventionally, hybrid simulation programs were implemented by embedding a TS program into an EMT simulator, or vice versa [5], [9], and only serial interaction between the EMT and TS program is feasible, which affects the efficiency of the hybrid simulation tool. This embedding architecture is feasible if at least one of the programs are developed in house. Therefore, it is not applicable to the case where both programs are developed by third parties and the source code is not available. Moreover, strict coupling between the EMT and the TS program limits the potential evolution of the hybrid simulation tool. Two EMT and TS programs are integrated in a decoupled manner in [8], [11]. However, a clear architecture design is lacking and the interface is implemented by using the pipe technology instead of a more general communication protocol. In this research, a loosely decoupled architecture coupled with a generic interface concept is proposed for the developed hybrid simulation tool, which will be discussed in detail in Chapter 4.

2.2.2 Network Equivalent of the Detailed and External System

(1) Network equivalent of the external system in EMT simulation

Both Thévenin and Norton equivalent are the two major forms of equivalents used to represent the external system in an EMT simulator in previous research [6]. A majority of the equivalents used in previous work are at the fundamental frequency. The frequency
dependent network equivalent (FDNE) model [5], [37]-[40] is introduced for better modeling the characteristics of the external system in EMT simulation over a wide range of frequencies.

One outstanding limitation of these network equivalents is that they are derived based on the assumptions of three-phase balanced and sinusoidal waveform, and only the positive sequence information is represented in the EMT simulator, making them inadequate for simulations considering unsymmetrical faults. In the cases involving unsymmetrical fault conditions within the detailed system, the boundary between the detailed and the external systems has to be extended towards the external system to make sure the three phases are reasonably balanced at the boundary. The corresponding disadvantage of this approach is the enlarged extent of the detailed system and increased number of interface buses. Otherwise, significant errors would be introduced in hybrid simulation, as confirmed by the study in [12]. Moreover, for a large and meshed power system, the extent to which the detailed system has to be extended might significantly undermine the applicability of hybrid simulation. An example for illustrating the boundary extension will be given in Chapter 5. This issue has been solved in this research through a combination of a three-phase Thévenin equivalent of the external system in EMT simulation and a three-sequence transient stability simulation algorithm for the external system.

(2) Network equivalent of the detailed system in TS simulation

First, for representing the detailed system in the TS simulation, a fundamental frequency network equivalent has to be used, as the TS simulation is based on the fundamental frequency, phasor model. RMS value based equivalents were confirmed to be generally
not a good equivalent for hybrid simulation, due to the inclusion of harmonics and lack of phase information [3], [41].

Much work has been done for extracting the fundamental frequency, positive sequence values from distorted and unbalanced waveforms and identifying proper variables for equivalencing purpose [3],[4],[41]. Both the fast Fourier transform (FFT) and curve fitting algorithm (CFA) have been used for extracting fundamental frequency data. Although FFT is more computationally burdensome compared to CFA, FFT has an advantage over CFA for processing current data that contains a DC offset component [41], which commonly exists during the fault and for a short period after the fault is cleared. It should be noted that FFT requires sampling data series of one cycle period to extract the fundamental frequency component, while CFA requires that of at least half of a cycle [41].

Regarding the network equivalent type, various types have been proposed so far, including voltage source, power injection, current source, Thévenin equivalent and Norton equivalent [4].

2.2.3 Interaction Protocol

Interaction protocol relates to how the EMT and TS simulators interact with each other through periodic exchange of the network equivalents, in order to achieve a simulation result close to that of simulating the whole system in detail. There are mainly two interaction protocols used in previous research, i.e., the serial and parallel protocol [11]. With the serial protocol, each simulator can use the updated equivalent data from the other side for the next time step of the simulation. Several variations of the serial type interaction protocol are proposed in [13]. However, with the serial protocol, one simulator must wait
until the other completes the simulation of one interaction period length and transfers the equivalent data, which becomes a performance bottleneck for hybrid simulation [11]. To overcome this performance issue, several types of parallel protocols have been proposed [11]. The parallel protocol proposed in [8] requires data exchange for each iteration of one TS simulation step, which not only makes the data exchange process very complicated, but also is impractical for most existing commercial EMT simulators. The parallel protocol proposed in [9] is relatively easy to implement. However, it may cause significant errors when the detailed system is subjected to a large disturbance. The equivalents of the external system may not reflect the disturbances within the detailed system in a timely manner, because both simulators use the simulation results of the previous interaction step to update the equivalents used in the following step. In an effort to combine the advantages of both types, an improved interaction protocol scheme, which flexibly combines both the serial and parallel protocols, is proposed in this research and will be discussed in Chapter 3.

Regarding the necessity of iteration of the EMT and TS simulations for each interaction, the study in [12] confirmed that hybrid simulation without iteration could produce results without noticeable differences from that with iterations, if network equivalents on both sides are properly chosen.

2.2.4 Identify the Boundary Between the Detailed and the External Systems

In previous work, the boundary between the detailed and external system had to be selected to make sure that the phase imbalance and waveform distortion at boundary buses are at acceptable levels [3], [4], [11], in order to comply with the assumptions of the positive sequence based TS simulation.
Previous research on hybrid simulation focused on applications to HVDC and FACTS systems. In these applications, the total number of the devices of special concern that needed to be modeled in detail was limited and the boundary selection process was relatively intuitive. The device connection bus(es) were selected as the boundary [3] or the boundary was extended several buses away from the connection bus(es) in order to have a more balanced condition at the boundary [4]. No general method has been proposed in the literature to determine the extent of the detailed system. The determination of the extent of the detailed system requires some prior knowledge of the system to be studied, otherwise a trial-and-error approach has to be used. In addition, the extent of the detailed system is highly dependent on the study case and the phenomenon of interest.

For a detailed FIDVR study, the study focus is not limited to one or several devices, but includes a number of A/C units, which are severely affected and potentially stall due to a disturbance within the detailed system. However, unlike a specific HVDC system or FACTS device, the A/C motors are widely dispersed and their connection points are located at the distribution feeder level. Therefore, a special process is required to determine the boundary between the detailed and the external systems for FIDVR studies. A short circuit analysis based approach is proposed for identifying the boundary of the detailed system, based on the idea of determining the stalling voltage threshold of A/C motors. This topic will be discussed in Chapter 5.
CHAPTER 3

HYBRID SIMULATION WITH THREE-PHASE/THREE-SEQUENCE NETWORK EQUIVALENTS AND A COMBINED INTERACTION PROTOCOL

3.1 Three-Phase Thévenin Equivalent of the External System

A three-phase (multi-port) Thévenin equivalent is used to represent the external system in the EMT simulation, as shown in Fig. 3.1. The equivalent includes two parts, the open circuit voltages and the equivalent impedances viewed at the terminals. The equivalent is updated at each interaction step based on the conditions of the external system at that instant. If the faults of concern occur within the detailed system, the topology of the external system does not change, thus, the equivalent impedance part can be assumed constant during the simulation. The process of building the three-phase Thévenin equivalent is carried out in five steps as shown in Fig. 3.2.

Fig. 3.1 Detailed system interfaced with a three-phase Thévenin equivalent of the external system
A three-sequence, full network model and boundary configuration

Form three sequence admittance matrices of the external system

Calculate three sequence Norton equivalent admittance matrices for the external system

Perform source transformation to obtain the objective three-phase Thévenin equivalent

Convert the three-sequence Norton equivalent to three-phase Norton equivalent

Build a three-sequence Norton equivalent for the external system

Fig. 3.2 The procedure of building a three-phase Thévenin equivalent

**Step (1): Form the three sequence admittance matrices of the external system**

To obtain the three-phase Thévenin equivalent of the external system, the study case should be modeled in three sequences, instead of positive sequence. Suppose the extent of the detailed system and the boundary buses are known, all the branches and buses, except the boundary buses, within the detailed system are set out of service. Then the three sequence admittance matrices of the external system are built separately using the corresponding sequence network models. The positive sequence admittance matrix $Y_{ext}^{(1)}$ can be built using the existing positive sequence TS algorithm, while the negative-sequence admittance matrix $Y_{ext}^{(2)}$ and zero-sequence admittance matrix $Y_{ext}^{(0)}$ can be formulated by the short circuit analysis program.

**Step (2): Calculate three sequence Norton equivalent admittance matrices for the external system**

Suppose there are $m$ interface buses at the boundary between the detailed system and the external system. To derive three sequence equivalent admittance matrices for the external system from $Y_{ext}^{(1)}$, $Y_{ext}^{(2)}$ and $Y_{ext}^{(0)}$, three sequence equivalent impedance matrices are calculated first based on their physical definitions by utilizing the sparse matrix
linear equation solver in the TS simulation program. Subsequently, these impedance matrices are converted to the corresponding admittance matrices.

An equivalent bus impedance matrix for the sequence \( s \) is a \( m \times m \) matrix in a form shown in (3.1)

\[
Z_T^{(s)} = \begin{bmatrix}
Z_{11}^{(s)} & \cdots & Z_{1m}^{(s)} \\
\vdots & \ddots & \vdots \\
Z_{m1}^{(s)} & \cdots & Z_{mm}^{(s)}
\end{bmatrix}, s \in \{1, 2, 0\}
\] (3.1)

where the superscripts 1, 2 and 0 represent the positive-, negative- and zero-sequence respectively. Entries in \( Z_T^{(s)} \) are calculated based on their definitions as follows

\[
Z_{ii}^{(s)} = \left. \frac{V_i^{(s)}}{I_i^{(s)}} \right|_{I_k^{(s)} = 0} \quad (3.2)
\]

\[
Z_{ji}^{(s)} = \left. \frac{V_j^{(s)}}{I_i^{(s)}} \right|_{I_k^{(s)} = 0} \quad (3.3)
\]

with \( i \in B, j \in B, k \in B \cup E \) and \( k \neq i \)

where \( B \) denotes a set of the boundary buses; \( E \) denotes a set of the buses in the external system except the boundary buses; \( Z_{ii}^{(s)} \) is a sequence self-impedance of bus \( i \); \( Z_{ji}^{(s)} \) is a sequence mutual impedance between bus \( j \) and bus \( i \); \( I_i^{(s)} \) and \( I_k^{(s)} \) are the sequence current injections at boundary bus \( i \) and \( k \), respectively; the sequence voltages \( V_i^{(s)} \) and \( V_j^{(s)} \) of boundary buses \( i \) and \( j \) can be obtained by solving (3.4) with only the sequence current injection at bus \( i \) \( I_i^{(s)} = 1 \) and other entries in the vector \( I^{(s)} \) being zeros (i.e., \( I_k^{(s)} = 0, \forall k \neq i \)).

\[
Y_{ext}^{(s)} V^{(s)} = I^{(s)} \quad (3.4)
\]
where \( I^{(s)} \) is a vector of bus sequence current injections of the external system, \( V^{(s)} \) is a vector of bus sequence voltages of the external system.

Solving (3.2)-(3.3) yields \( Z_{ii}^{(s)} = V_i^{(s)} \) and \( Z_{ji}^{(s)} = V_j^{(s)} \). All boundary bus impedances in the three sequence equivalent impedance matrices can be calculated in this manner.

Subsequently, a sequence Norton equivalent admittance matrix denoted by \( Y_N^{(s)} \) can be obtained using (3.5). It is worth noting that the number of boundary buses is usually small (less than 10), so the inversion operation is computationally trivial.

\[
Y_N^{(s)} = Z_T^{(s)^{-1}} \tag{3.5}
\]

**Step (3): Build three-sequence Norton equivalent of the external system**

Combining all Norton equivalents of three sequences, a three-sequence Norton equivalent of the external system viewed at the boundary bus(es) is obtained as:

\[
I_N^{120} = Y_N^{120}V_{TS}^{120} - I_{EMT}^{120} \tag{3.6}
\]

\[
Y_{Nik}^{120} = \begin{bmatrix}
Y_{Nik}^{(1)} & 0 & 0 \\
0 & Y_{Nik}^{(2)} & 0 \\
0 & 0 & Y_{Nik}^{(0)}
\end{bmatrix} \tag{3.7}
\]

where \( I_N^{120} \) is a \((3m \times 1)\) vector representing the three-sequence Norton equivalent current source; \( Y_N^{120} \) is a block matrix representing the three-sequence Norton admittance matrix of the external system; \( Y_{Nik}^{120} \) is \(3 \times 3\) submatrix of \( Y_N^{120} \), representing an entry at the \( i \)th row and \( k \)th column of \( Y_N^{120} \); \( V_{TS}^{120} \) is a \((3m \times 1)\) vector and denotes the three-sequence voltages of the boundary buses obtained from the TS simulation; \( I_{EMT}^{120} \) is a \((3m \times 1)\) vector of the three-sequence current injections at the boundary bus(es). At the data preparation stage,
the entries of $I_{EMT}^{120}$ are obtained from the power flow result of the full network. During hybrid simulation, $I_{EMT}^{120}$ is obtained from the EMT simulation.

**Step (4): Obtain the three-phase Norton equivalent of the external system**

A three-sequence to three-phase transformation is required to derive the three-phase Norton equivalent from the three-sequence representation. The transformation is carried out in an element-wise manner as follows:

$$I_{Ni}^{abc} = S I_{Ni}^{120}$$  \hspace{1cm} (3.8)

$$y_i^{abc} = S y_i^{120} S^{-1}$$  \hspace{1cm} (3.9)

$$y_{ik}^{abc} = S y_{ik}^{120} S^{-1}$$  \hspace{1cm} (3.10)

$$S = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}, \quad a = e^{j2\pi/3}$$  \hspace{1cm} (3.11)

where $S$ is a $3 \times 3$ three-sequence to three-phase transformation matrix; $I_{Ni}^{120}$ and $I_{Ni}^{abc}$ denote the Norton equivalent current source of boundary bus $i$ in three-sequence and three-phase, respectively. $y_i^{120}$ and $y_i^{abc}$ are the primitive self-admittance of boundary bus $i$ in three-sequence and three-phase, respectively. An illustrative diagram representing $y_i^{abc}$ is shown in Fig. 3.3. $y_{ik}^{120}$ and $y_{ik}^{abc}$ are the three-sequence and three-phase primitive mutual admittance between the boundary buses $i$ and $k$, respectively. After the steps discussed above, the resulting equivalent is a three-phase Norton equivalent, as shown in Fig. 3.4.

**Step (5): Obtain the three-phase Thévenin equivalent of the external system**

When the three-phase Norton equivalent obtained in step (4) is represented in some existing EMT simulators such as PSCAD, some actual modeling issues arise. In PSCAD, only the magnitude of the single-phase current source component is adjustable while the
phase has to be fixed during simulation, whereas the single-phase voltage source component is allowed to adjust both the magnitude and the phase angle externally.

Fig. 3.3 A generic, three-phase representation of a bus primitive admittance

Considering this modeling limitation, the Norton equivalent for each phase needs to be further converted to a single-phase Thévenin equivalent by using (3.12)-(3.13)

\[
V_{Ti}^\phi = I_{Ni}^\phi / y_{i}^\phi \\
z_{i}^\phi = 1 / y_{i}^\phi
\]

where \( \phi \) stands for one of the three phases; \( y_{i}^\phi \) and \( z_{i}^\phi \) are the primitive self-admittance and self-impedance of phase \( \phi \) of boundary bus \( i \), respectively; \( I_{Ni}^\phi \) is the Norton equivalent current source of phase \( \phi \) and \( V_{Ti}^\phi \) is the phase Thévenin voltage source of bus \( i \).
Subsequently, the phase-to-phase primitive mutual impedances of a boundary bus and the three-phase primitive mutual impedances among the boundary buses are obtained from the corresponding admittances based on (3.14) and (3.15).

\[
\begin{align*}
Z_i^\phi = & \frac{1}{Y_i^\phi} \\
Z_{i_k}^{abc} = & Y_{i_k}^{abc}^{-1}
\end{align*}
\]

(3.14) (3.15)

where \( \varphi \) stand for one of the three phases and \( \phi \neq \varphi \); \( Y_i^\phi \) and \( Z_i^\phi \) are the phase-to-phase primitive mutual impedances and admittances, respectively, between the phases \( \phi \) and \( \varphi \) of boundary bus \( i \); \( Z_{i_k}^{abc} \) is the three-phase primitive mutual impedance between the boundary buses \( i \) and \( k \). With all the five steps completed, the three-phase Thévenin equivalent of the external system is obtained and shown in Fig. 3.5.

![Multi-port three-phase Thévenin equivalent](image)

Fig. 3.5 A multi-port three-phase Thévenin equivalent
The new connections among the boundary buses \(z_{ik}^{abc}\) are corresponding to the mathematical fill-in terms in the equivalents. In order to lessen the modeling and simulation complexity without compromising the accuracy, only the connections whose corresponding positive sequence impedances are less than a threshold (5 pu is used in this research) are preserved and modeled in the EMT simulator. Another issue relates to the new connections between two boundary buses of different base voltages. If the difference between values of their positive and negative sequence impedances are negligible, which generally is true, then using the three-sequence representation is easier than three-phase. A three-phase two-winding transformer model can be used to represent these connections. These transformers are modeled as grounded wye-grounded wye connection with a grounding impedance at the high voltage side as shown in Fig. 3.6. Suppose the positive- and zero-sequence impedances of a new connection between boundary buses \(i\) and \(k\) are \(z_{ik}^{(1)}\) and \(z_{ik}^{(0)}\), respectively, then the grounding impedance is \((z_{ik}^{(0)} - z_{ik}^{(1)})/3\).

![Diagram](image)

Fig. 3.6 Representing a new connection between two boundary buses of different base voltages as a two-winding transformer

If the differences between the positive and the negative impedances are non-negligible, the new connection should be represented by using a combination of a three-phase line model and a two-winding transformer model.
3.2 Three-Sequence Equivalent of the Detailed System

There are several approaches for representing detailed systems in TS simulation, including current sources, constant PQ loads and Norton or Thévenin equivalents [9]. It should be noted that it is difficult to derive the Norton admittance or Thévenin impedance matrix of the detailed system, because there may be power electronic devices in the detailed system and such matrix data is not accessible from most existing EMT simulators. Three-sequence current sources, as shown in Fig. 3.7, are used for the following reasons:

1) The current source representation seamlessly integrates into the network solution step of the TS simulation.

2) In some existing EMT simulators such as PSCAD, an FFT component is available and can be directly used to extract the fundamental frequency, three-sequence current magnitude and phase values, as shown in Fig. 3.8.

Fig. 3.7 The detailed system is represented by three-sequence current sources in TS simulation.
Fig. 3.8 Extracting fundamental frequency, three-sequence current injections using the FFT component in PSCAD

3.3 Improved Interaction Protocol between the EMT and TS Simulators

3.3.1 A Combined Interaction Protocol

There are mainly two types of interaction protocols used for exchanging data between the TS and the EMT programs, i.e., the serial and the parallel type protocols, as shown in Fig. 3.9. The interaction period is $\Delta T$, which is usually set to be the same as the integration time step in TS simulation.

Figure 3.9(a) demonstrates the parallel interaction protocol—direct data exchange in both directions before each TS simulation step. This interaction method is simple and easy to implement. Both programs run asynchronously for each $\Delta T$ period, thus good simulation efficiency is achieved. However, The TS program uses the previous time step simulation results to update the equivalents for the following time step. This may result in large discrepancies, particularly during the period when the system experiences significant changes, as the equivalents may have not been updated in a timely fashion.
The serial interaction protocol is depicted in Fig. 3.9(b). Different from the parallel protocol, the TS program always uses the latest available information from the EMT side to perform one-step simulation and then update the equivalents for the EMT simulation with the new results before sending it back to the EMT program. However, each program must wait for the other to complete the simulation of $\Delta T$ length before proceeding to the next step. Therefore, the simulation efficiency is worse than that with the parallel protocol.

In an effort to combine the advantages of both types of protocols, a combined interaction protocol shown in Fig. 3.10 is proposed. The combined protocol is based on the following observation: fast dynamics and significant system changes usually occur during the faulted period and last for a short period after the fault is cleared. To better capture the

Fig. 3.9 Interaction protocols: (a) parallel, (b) serial
fast dynamics in the system, the serial protocol should be used. For the rest of the simulation period, the slow dynamics dominates and the parallel protocol can be used to achieve good efficiency without degrading the accuracy.

In this research, the serial and the parallel interaction protocols are implemented as shown in Fig. 3.11 and Fig. 3.12 respectively. In both figures, $t$ denotes the start time for the processing step, $\Delta T$ is the TS simulation time step as well as the EMT-TS interaction time step. $I_{EMT(t)}^{120}$ and $I_{EMT(t-\Delta T)}^{120}$ are the three-sequence current injection vectors sent from the EMT side for the present time step and previous time step, respectively.

If a significant change within the detailed system is detected, a serial interaction protocol is used for this time step. As shown in Fig. 3.11, the operation involves 5 steps. The first step is data transfer via socket and pre-processing. Then, in step (2), $I_{EMT(t)}^{120}$ is used as the input for the three-sequence TS simulation and a new three-sequence voltage vector of the boundary buses is obtained. Subsequently, the three-sequence Thévenin equivalent voltages $V_{abc}^{120}_{T(t+\Delta T)}$ are derived by the network equivalent helper using $I_{EMT(t)}^{120}$ and $V_{TS(t+\Delta T)}^{120}$ in step (3) and sent back to EMT in step (4). On receiving $V_{abc}^{120}_{T(t+\Delta T)}$, EMT
Fig. 3.11 The implementation of EMT-TS hybrid simulation with the serial interaction protocol
Fig. 3.12 One interaction step of the developed EMT-TS hybrid simulation with the parallel interaction protocol.
continues the step (5), which usually consists of hundreds of EMT simulation steps. Considering the computational complexity of each step, it is obvious that step (2) and step (5) are the two most time-consuming steps.

Otherwise, the parallel protocol shown in Fig. 3.12 is used. The step for calculating Thévenin equivalent voltage (step (b)) is executed after step (a), while the time-consuming step (d) is moved to the last step on TS side. With this data flow, the Thévenin voltage sources are calculated using the previous step bus voltages and sent back to EMT simulator immediately, such that step (d) and (e) can be run simultaneously. It can be observed that the main implementation difference between the two interaction protocols lies in the execution sequence of the subroutines in the TS program, therefore, switching between the two interaction protocols only needs to change the execution logic of the subroutines and is easy to implement.

3.3.2 An Algorithm for Controlling Protocol Switching

One remaining challenge of the combined interaction protocol is to automatically determine when the protocol switching operation should be performed. To address this challenge, an algorithm is proposed for selecting the processing step interaction protocol based on the last step protocol and detection of any large transient event within the detailed system. Details of the design and implementation will be discussed in this section.

(1) Sequence current injections are used for determining protocol switching

First, based on the theory of power system fault analysis and power system protection, current is a good, if not the best, parameter for detecting the fault or other transient conditions in power systems, compared to other measurable parameters in the system, such
as voltage, frequency and power. Both the current magnitude and the existence of large negative- or zero-sequence current are good indications of abnormality in a transmission system. Second, as discussed in the previous network equivalent section, the sequence current injections are extracted and sent from the EMT side to the TS side at each interaction instant, reusing it for protocol switching control help simplify the interface design and reduce the communication overhead.

(2) Use of the maximum rate of change of current injections as the indicator

As discussed in section 3.3.1, it is only during the period when the system is undergoing fast dynamics that the hybrid simulation needs to switch to the serial interaction protocol. Under such a condition, there are usually two obvious features that can be observed in the simulation results: (a) some of the monitored parameters deviate significantly from their normal values; (b) some parameters change faster than under normal or slow dynamic conditions.

For the feature (a), the deviation magnitudes of the monitoring parameters could be used; however, it is difficult to determine a general deviation magnitude, considering the enormous differences among different study cases and disturbances. In addition, it fails to provide the information for determining whether the system is undergoing a fast transient or slow dynamics, as there might be some cases where the selected parameter might sustain depressed or recover very slowly after a fault is cleared.

For the feature (b), the rates of change of the magnitudes of the key operation parameters in power system, including voltage, current and power, are zero under a steady state condition, or very small when the system experience slow dynamics. In general, their
rates of change suddenly become notably larger than their normal values when there is a severe disturbance or fault in the vicinity. Thus, a threshold is easier to determine for this feature than the feature (a). A positive, small value, which can reasonably “distinguish” the fast dynamics from the steady state and slow dynamics, can be used as the threshold $\varepsilon$. The maximum rate of change of the monitoring parameters is compared with the threshold $\varepsilon$ to decide which one of the two interaction protocols is appropriate.

Based on the previous discussions, the detection of fast dynamics within the detailed system is based on the maximum rate of change of the three-sequence current injections at the boundary, which is denoted by $R_{EMT}^{120}(t)$ and defined by (3.16).

$$R_{EMT}^{120}(t) = \max\left( \max_{i} \max_{s \in \{1, 2, 0\}} \left( \frac{I_{EMT}^{(s)}(i, t) - I_{EMT}^{(s)}(i, t - \Delta T)}{I_{EMT}^{(1)}(i, t - \Delta T)} \right) \right) / \Delta T$$  \hspace{1cm} (3.16)

where $i$ denotes one of the boundary buses, $s$ represents a sequence and it may be positive, negative or zero sequence; $I_{EMT}^{(s)}(i, t)$ is the current injection of sequence $s$ at the boundary bus $i$ at time $t$; $\Delta T$ is interaction time step.

(3) Delay function to control switching from serial to parallel protocol

Before switching the protocol from serial type to parallel type, the algorithm needs to make sure that the fault period has been completed. However, generally, the rate of change of the boundary injection currents during the fault period would become smaller after reaching the peak, as illustrated by Fig. 3.13. The fault is applied at 1.0 s and cleared at 1.07 s. If the solid black line in Fig. 3.13 were the maximum rate of change threshold, the protocol control would switch to parallel at 1.045 s and switch from parallel back to
serial at 1.075 s. The switching actions during the fault period are not desirable. This indicates a shortcoming of the rate of change based approach. Therefore, a delay function is introduced to fix the known issue of “rate of change settling down near the peak”. With this delay function design, the maximum rate of change $R_{EMT(t)}^{120}$ must be consecutively below the threshold for at least a period defined by the delay setting, before switching from the serial protocol to the parallel protocol. Introduction of this delay function also adds more flexibility in selecting the threshold $\varepsilon$.

![Diagram](image)

**Fig. 3.13** An example for illustrating the necessity of a delay block in protocol switching control design

**4) Implementation**

The logic of the switching algorithm is illustrated by Fig. 3.14. Whenever $R_{EMT(t)}^{120}$ is larger than the threshold $\varepsilon$, the serial protocol is used such that the large transients within the detailed system can be reflected in a timely manner in the TS simulation. Otherwise,
the parallel protocol is used. On the other hand, before the switching from the serial protocol to the parallel protocol is triggered, the delay function is enabled. The serial protocol is used until the preset delayed time is reached.

![Diagram of control algorithm](image)

Fig. 3.14 The logic of protocol switching control algorithm

(5) Parameter selection

First, based on (3.16), the threshold $\varepsilon$ is proportional to the maximum tolerable step change of three sequence current injections for a given $\Delta T$ when using parallel interaction protocol. In this regard, 10% change in the three-sequence current injections between two consecutive interaction steps can be reasonably selected as the maximum. On the other hand, a too small step change might not be able to distinguish the fast and the slow dynamic conditions. Thus, 2%-10% step change is a recommended selection range in this research. Once the maximum change is determined, the threshold can be determined by dividing the value of maximum change by the interaction time step.

For the delay time setting, based on the characteristics of power system transients and simulation experiences, the delay setting should be at least half of the fault period. For example, the delay time is recommended to be at least 2 cycles for a 4-cycle fault.
3.4 Summary

In this chapter, two techniques to improve the hybrid simulation are proposed. First, a three-phase, multi-port Thévenin network equivalent and a three-sequence current source equivalent are proposed for representing the external system and the detailed system, respectively, in the proposed EMT-TS hybrid simulation approach. With these equivalents for hybrid simulation, both balanced and unbalanced faults can be studied within the detailed system without the boundary condition contraints. Second, to improve the simulation performance of hybrid simulation while maintaining a good accuracy, a serial and parallel combined interaction protocol is proposed, along with an automatic protocol switching algorithm.
CHAPTER 4

DEVELOPMENT OF A HYBRID SIMULATION TOOL: OPENHYBRIDSIM

The two key improvements discussed in Chapter 3 will be applied to the development of an open source hybrid simulation tool—OpenHybridSim. Details of the development, including the overall design, main components of the tool and interfacing with an EMT simulator, will be presented in this chapter.

4.1 Overall Design of OpenHybridSim

OpenHybridSim is designed with a decoupled architecture that enables flexibility. Its architecture is shown in Fig. 4.1. This tool includes four modules: the hybrid simulation manager, the core engine of the open source power system simulator InterPSS [32], the network equivalent helper, and the socket communication framework.

![Fig. 4.1 The architecture of OpenHybridSim](image)

InterPSS is an open source software for power system analysis and simulation. This software has an open and flexibly coupled system architecture. It is developed using object-oriented programming (OOP). The models and algorithms within InterPSS can be flexibly modified and extended. Moreover, the software itself can be easily integrated into other
systems [32]. Network models and algorithms for power flow, short circuit analysis and transient stability simulation have been developed in InterPSS. In view of these available features, InterPSS is used as a TS program for the proposed hybrid simulation tool.

The core functions of the hybrid simulation manager include determining the processing step interaction protocol, managing data conversion and interchange among modules on the TS side. A three-sequence TS simulation algorithm has been developed based on the InterPSS core engine. The primary objective of the network equivalent helper is to prepare a Thévenin equivalent for the detailed system modeling at the modeling preparation stage and update the equivalent for the EMT simulation during hybrid simulation.

For each interaction between the two simulators, sequence current injection data is first sent from the EMT simulator to OpenHybridSim. Upon receiving the data, the hybrid simulation manager determines a proper protocol for this interaction, based on the algorithm proposed in Chapter 3. If the serial protocol is selected, the equivalent data from the EMT simulator is input into the InterPSS core engine to perform one time step TS simulation, and then the external system Thévenin equivalent is updated and sent back to the EMT simulator via the socket server. Otherwise, the Thévenin equivalent is updated first by the network equivalent helper, and the TS simulation step is postponed to the last step.

4.2 Development of OpenHybridSim

4.2.1 A Three-Sequence TS simulation

In accordance with the use of the three-phase Thévenin equivalent for representing the external system, all components in the external system, including the generators, trans-
mission elements and loads, are represented using their three-sequence components. Correspondingly, a three-sequence based TS simulation algorithm is developed, as depicted in Fig. 4.2. The algorithm is composed of the conventional positive sequence TS algorithm and a sequence network solver. The sequence network solver is developed based on the existing short circuit analysis module of InterPSS. It calculates the negative- and zero-sequence voltages with the sequence current injections at the boundary buses and other buses inside the external system, if any. The algebraic equations shown in Fig. 4.2 can be described by (4.1) and (4.2), respectively.

\[
\begin{align*}
Y_{ext}^{(2)} V_{ext}^{(2)} &= I_{ext}^{(2)} \quad (4.1) \\
Y_{ext}^{(0)} V_{ext}^{(0)} &= I_{ext}^{(0)} \quad (4.2)
\end{align*}
\]

where the subscript \text{ext} denotes external system, \(V_{ext}^{(2)}\) and \(V_{ext}^{(0)}\) are the vectors of negative- and zero-sequence voltages, respectively; \(Y_{ext}^{(2)}\) and \(Y_{ext}^{(0)}\) are the negative- and zero-sequence admittance matrices of the external system, respectively; \(I_{ext}^{(2)}\) and \(I_{ext}^{(0)}\) are vectors of the negative- and zero-sequence bus current injections, respectively. \(I_{ext}^{(2)}\) and \(I_{ext}^{(0)}\) include the sequence current injections at the boundary buses obtained from the EMT simulation and sequence current injections at the buses inside the external system, if any.

It should be noted that when the fault is applied within the detailed system and the topology of the external system is unchanged during the simulation, factorization of the three sequence admittance matrices is required for only once. In addition, these sequence networks are decoupled and can be solved independently. To further improve the compu-
tational efficiency, the sequence network solver could be disabled when there are negligible negative- and zero-sequence current injections at the boundary, and it could be enabled on detecting non-negligible negative and zero sequence current injections.

\[
\begin{align*}
\dot{x}(t) &= f(x(t), y^{(1)}(t)) \\
x(t + \Delta T) &= x(t) + \dot{x}(t)\Delta T \\
0 &= g_1(x(t + \Delta T), y^{(1)}_{(t+\Delta T)}, I^{(1)}_{EMT(t)})
\end{align*}
\]

\[
\begin{align*}
0 &= g_2(y^{(2)}_{(t+\Delta T)}, I^{(2)}_{EMT(t)}) \\
0 &= g_0(y^{(0)}_{(t+\Delta T)}, I^{(0)}_{EMT(t)})
\end{align*}
\]

Fig. 4.2 A three-sequence based TS simulation algorithm

4.2.2 Creation and Initialization of External System

To ease the burden of data preparation and facilitate the application of hybrid simulation, the external system is automatically created and initialized from a given base case. The creation and initialization process is as follows:

1) Run power flow with the whole system, then calculate the positive sequence current injections from the detailed system into the external system based on the boundary configuration information.

2) With the boundary information, apply the depth first search (DFS) algorithm to the base case to identify all buses and branches within the detailed system and set them out of service.

3) Initialize the positive sequence part of the external system using the existing initialization function of the TS program, with the detailed system represented...
by the current injections calculated in step 1). Both the negative- and zero-sequence current injections are assumed to be zero at the initialization stage. The negative- and zero-sequence admittance matrices of the external system are factorized and ready for use during hybrid simulation.

4.2.3 Procedures of Conducting Hybrid Simulation

Some screenshots of the GUI of the developed tool are shown in Figs. 4.3 and 4.4. The procedure for conducting hybrid simulation using the tool is shown in Fig. 4.5.

Fig. 4.3 Importing data through the GUI of OpenHybridSim

Fig. 4.4 Configuration for hybrid simulation in the GUI of OpenHybridSim

47
Fig. 4.5 The flow chart of running hybrid simulation with OpenHybridSim
4.3 Interfacing with an EMT Simulator

One objective of this tool is to enable users to flexibly integrate with any EMT simulator. This objective is fulfilled by the use of socket communication, which will be presented in the following section, and a simple logic required to be implemented in the socket component in the EMT simulator shown in Fig. 4.1. The logic is shown in Fig. 4.6.

![Diagram](image)

**Fig. 4.6 Logic of the socket component in an EMT simulator**

### 4.3.1 A Socket-based Communication Framework Protocol

The socket technology is widely used for inter-process communication (IPC) between two programs, and the socket programming interface is supported by all modern operating systems. In addition, socket APIs are standard in almost all mainstream programming languages. Thus, the socket technology is chosen as the communication “bridge” between the EMT simulator and OpenHybridSim, with a socket client on the EMT side and a socket server in OpenHybridSim.
When the socket technology is combined with transmission control protocol/Internet protocol (TCP/IP) communication, a socket can not only integrate two programs on the same computer, but also connect simulation programs running on different computers through the Internet. Thus, the communication framework enables OpenHybridSim to have a good potential of running hybrid simulation in a distributed manner, as illustrated in Fig. 4.7. The architecture of the parallel hybrid simulation is a typical client-server model. The server is built on the TS simulation side and can create several (up to tens or even hundreds, depending on the capability of the server machine) sockets to communicate with multiple EMT simulation clients concurrently.

![Diagram](image)

Fig. 4.7 A perspective distributed hybrid simulation with OpenHybridSim

4.3.2 An Interface between OpenHybridSim and PSCAD

PSCAD is one of the widely used, comprehensive EMT simulators. An interface between OpenHybridSim and PSCAD has been developed and this interface is introduced here as an interfacing example. The interface mainly involves a socket client developed as a component in PSCAD, as shown in Fig. 4.8. The basic socket communication function is based on [43], and modifications and enhancements have been made for hybrid simulation applications. The logic of the socket component shown in Fig. 4.6 is implemented in
the “script” section of the component definition in PSCAD. Features of the socket component include:

- Two ends: a sending end for passing data from PSCAD side to the TS side and a receiving end for catching and saving the data from TS side.
- The number of data at both ends must be explicitly specified.
- IP address and port must be set properly beforehand. The combination of both forms a socket address.
- Time delay: an initialization process is required for EMT type simulations, therefore, a time delay must be properly set to make sure the detailed system in PSCAD has been successfully initialized before starting hybrid simulation.
- Time step: the interaction time step for hybrid simulation. It is usually set to be the same as TS simulation time step.

![Fig. 4.8 Socket component developed in PSCAD](image-url)
4.4 Test Cases

A hybrid simulation platform has been built by integrating the developed tool with PSCAD. The proposed network equivalents and the combined interaction protocol are tested based on the hybrid simulation platform. The simulation results are compared with that obtained by all EMT simulation with PSCAD. The IEEE 9 bus system [44] shown in Fig. 4.9 is used in the test cases. The data of the system is provided in Appendix-A. The entire system is also modeled in PSCAD with the generators modeled using the E-TRAN library [45].

![One-line diagram of the IEEE 9 bus system](image)

Fig. 4.9 One-line diagram of the IEEE 9 bus system

An EMT simulation time step is 50 microseconds (µs) by default. However, it is set to be 20 µs whenever there are detailed single-phase air conditioner compressor motors [17] modeled in the detailed system. Both the TS simulation time step and the interaction
time step are 5 ms. The time delay for protocol switching from serial to parallel is set to be 2 cycles, as the faults in the following test cases last for 4 cycles.

Besides visual judgment of the comparison results, the accuracy of the proposed hybrid simulation approach is also investigated by calculating the average and maximum differences in simulation results with respect to PSCAD simulation, which are denoted by $D_{avg}$ and $D_{max}$, respectively.

4.4.1 Case 1: The Interaction Protocols

First, the hybrid simulation is conducted with only bus 5 and the load connected to it as the detailed system. Hence, bus 5 is the only boundary bus. The load connected to bus 5 is modeled as an impedance. A three-phase fault is applied at bus 5 at 0.1 s and cleared after 0.05 s. The results are shown in Fig. 4.10. It is observed that positive sequence currents injected into the external system through bus 5 for both the serial and the combined protocols agree quite well with that obtained by PSCAD simulation, while the parallel protocol results in a larger difference. In addition, as shown in Fig. 4.10, the proposed index $R_{EMT}^{120}(t)$ correctly reflects severe changes in the detailed system during the fault period and thereby the proposed protocol switching control algorithm promptly switches to the serial protocol. After the fault is cleared and fast dynamics settle, the switching control algorithm switches back to the parallel protocol.

The sensitivity of the protocol switching control to the threshold is analyzed and the result is shown in Fig. 4.11. For the thresholds from 0.004 to 0.02 (corresponding to 2%-10% change per each interaction step), the protocol switching control behaves correctly, with only slight differences in the time of switching back to the parallel type. In
contrast, the threshold 0.04 leads to protocol switching back to the parallel type during the fault period. This preliminary result indicates that the protocol switching is not sensitive to the threshold if it is within the range of 0.004 to 0.02.

Fig. 4.10 Interaction protocol testing results: (a) positive sequence current injections at bus 5; (b) current maximum rate of change, switching threshold (0.004) and the protocol switching signal for the proposed combined protocol (0 for parallel, 1 for serial)
### Table 4.1 Statistics of the simulation difference when using different interaction protocols

<table>
<thead>
<tr>
<th>Interaction protocol</th>
<th>$D_{avg}$/kA</th>
<th>$D_{max}$/kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>parallel</td>
<td>0.2500</td>
<td>1.4545</td>
</tr>
<tr>
<td>serial</td>
<td>0.1300</td>
<td>0.8038</td>
</tr>
<tr>
<td>combined</td>
<td>0.1302</td>
<td>0.8038</td>
</tr>
</tbody>
</table>

Fig. 4.11 Sensitivity of the protocol switching to the threshold selection (case 1)

#### 4.4.2 Case 2: Multi-Port Three-Phase Thévenin Equivalent

To further illustrate the functioning of the hybrid simulation process and to test the proposed multi-port three-phase Thévenin equivalent under unsymmetrical faults, the detailed system is expanded to include both bus 5 and the branch bus5-bus7, with the internal/external interface consisting of bus 5 and bus 7. In addition, the load at bus 5 is replaced by a detailed model down to the distribution feeders where the single-phase A/C compressor motors is connected, as shown in Fig. 4.12. The composite load model mimics the WECC composite load model [22] except that the A/C motor is represented by the detailed
single-phase induction motor developed in [17]. The composition and parameters of the
detailed load model are provided in Table 4.2. A single-line-to-ground fault is applied on
phase A of the 69 kV bus at 2.0 s and cleared after 4 cycles. The behavior of the parallel
and the proposed combined protocols are further compared. The parallel protocol under the
condition of fast dynamics leads to large spikes in the calculated Thévenin voltage shown
in Fig. 4.13 for the period right after the fault is applied and cleared. These are attributed

![Diagram of bus 5 and load model]

**Fig. 4.12 Detailed modeling of bus 5**

**Table 4.2 Composition of the composited load model**

<table>
<thead>
<tr>
<th>Load component</th>
<th>Steady state load (MW/MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Φ A/C motor, number = 1480/phase</td>
<td>7.0 + j2.5 MVA / phase*</td>
</tr>
<tr>
<td>3-Φ, constant torque motor (A), number = 275</td>
<td>4.1 + j2.0 MVA</td>
</tr>
<tr>
<td>3-Φ, variable torque and large inertia motor (B), number = 1</td>
<td>0.7 + j0.3 MVA</td>
</tr>
<tr>
<td>3-Φ, variable torque and low inertia motor (C), number = 1</td>
<td>0.4 + j0.2 MVA</td>
</tr>
<tr>
<td>Static load</td>
<td>14.1 + j4.2 MVA</td>
</tr>
</tbody>
</table>

* There are 1480 A/C units connected to each phase of the equivalent feeder.
Fig. 4.13 The magnitude of the phase A Thévenin voltage source of bus to the improper interaction timing. The TS program still uses the pre-fault voltage to calculate the Thévenin voltage for the first data exchange right after the fault, which results in erroneous (and much larger) equivalent voltages, and in turn produces a larger fault current in the subsequent steps.

Phase A current injection into bus 5 and three-phase voltages of bus 5 are shown in Fig. 4.14 and Fig. 4.15, receptively. A simulation difference statistic is also provided in Table 4.3. The speed of the A/C motors connected to the phase C of a feeder is shown in Fig. 16 to illustrate the response of the A/C compressor motor to the SLG fault. Fig. 4.17 shows the measured reactive part of the total load of bus 5 obtained by PSCAD and the proposed hybrid simulation with different interaction protocols and interaction time steps.

The three-phase voltage plots in Fig. 4.15 show a severe unbalanced condition of phase voltages on the boundary. Under such a condition, simulation results obtained by the developed platform with the combined protocol still match that of the PSCAD simulation quite well, demonstrating the effectiveness of the proposed three-phase Thévenin equivalent and validating the accuracy of the developed platform. In addition, the simulation results obtained by the hybrid simulation with the proposed combined interaction protocol
are consistently closer to that obtained by PSCAD compared to the parallel interaction protocol.

The comparison results shown in Fig. 4.17 suggest that the performance of the combined interaction protocol is more robust with respect to the interaction time step, compared to the parallel type. Thus, the combined interaction protocol provides more flexibility in selecting the TS simulation time step, whereas a small TS simulation time step has to be used when the parallel interaction protocol is adopted in order to maintain the simulation accuracy.

Fig. 4.14 The phase A current injection at bus 5 into the external system
Fig. 4.15 Three-phase voltages of bus 5
Table 4.3 Simulation result differences of different protocol for phase A voltage and current injection at bus 5

<table>
<thead>
<tr>
<th>Interaction protocol</th>
<th>$D_{avg}(V_a)/pu$</th>
<th>$D_{avg}(I_a)/pu$</th>
<th>$D_{max}(V_a)/pu$</th>
<th>$D_{max}(I_a)/pu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>parallel</td>
<td>0.041</td>
<td>0.068</td>
<td>0.416</td>
<td>1.029</td>
</tr>
<tr>
<td>combined</td>
<td>0.015</td>
<td>0.050</td>
<td>0.354</td>
<td>0.541</td>
</tr>
</tbody>
</table>

Fig. 4.16 Speed of the AC units connected to the phase C of a feeder

Fig. 4.17 The reactive part of the total load of bus 5 with different interaction protocols and interaction time steps
4.5 Summary

The details of the development of a new tool for hybrid simulation based on InterPSS are presented in this chapter. First, the overall design of the tool is presented and a decoupled architecture is adopted for the hybrid simulation platform. Then a three-sequence transient stability algorithm is proposed and developed by combining the positive sequence transient stability algorithm and a network solver for solving negative- and zero-sequence networks with current injections at the boundary buses. Procedures used in the tool for creating and initializing the external system are also outlined.

Hybrid simulations with the parallel, serial and combined interaction protocols are conducted and compared to full EMT simulations. Results verify that the combined interaction protocol is almost as accurate as the serial protocol. The automatic switching algorithm can identify the system slow and fast dynamic conditions correctly and make sure the tool switch to the right protocol. Lastly, the developed hybrid simulation platform is tested with a modified IEEE 9 bus system. Simulation results confirm that the proposed equivalents and the developed hybrid simulation tool can produce accurate results, under both symmetrical and unsymmetrical fault conditions.
CHAPTER 5
APPLICATION OF HYBRID SIMULATION TO A DETAILED FIDVR STUDY ON THE WECC SYSTEM

With A/C compressor motor models developed for planning studies and detailed simulation, in-depth knowledge of the FIDVR problem at the load component level is obtained. However, a better understanding of the FIDVR events from a system perspective is urgently needed. To develop such an understanding, dynamic responses of single-phase A/C compressor motors to unsymmetrical faults at the transmission system and the interaction between the transmission system and the distribution systems during a FIDVR event need to be examined. Detailed simulation of FIDVR events on power systems, which are subjected to this problem, is one feasible approach to fulfill this objective. A detailed FIDVR study of a region within the WECC system is conducted in this chapter, based on the developed hybrid simulation platform.

5.1 Overview of the WECC system

FIDVR events have been observed in several areas within the WECC system, e.g., Southern California and Arizona. In this study, a region within the WECC which is known to have experienced FIDVR events in recent years is chosen for this study. A summer peak case of the system is used, and its basic information is summarized in Table 5.1. The one-line diagram of this region and the surrounding area is depicted in Fig. 5.1. The buses 24138 and 24151 in Fig. 5.1 correspond to two 500 kV substations, where a large percentage of the loads are induction motors, and a majority of them are single-phase A/Cs, particularly, for the bus 24151. Thus, both substations are of primary interest in this study.
Table 5.1 Case summary of the WECC system

<table>
<thead>
<tr>
<th>Buses</th>
<th>Transmission lines</th>
<th>Generators</th>
<th>Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>15750</td>
<td>13715</td>
<td>3074</td>
<td>7787</td>
</tr>
</tbody>
</table>

For the sake of simplicity, the details of the sub-systems below 500 kV are not presented in Fig. 5.1, although some buses within these sub-systems are also connected to the northern and eastern parts of the system.

The first step in a detailed FIDVR study is to build an appropriate simulation model for hybrid simulation, based on the existing system planning model. The simulation model includes two parts, the external system and the detailed system. For the detailed system modeled in PSCAD, a specific modeling process is required as outlined in Fig. 5.2. The details of each step in the process will be discussed in the following three sections.
Fig. 5.2 Procedure of the detailed system modeling in PSCAD

5.2 Determining the Boundary of the Detailed System

The boundary of the detailed system is defined by the study area of special interest together with a suitable buffer zone. With the EMT-TS hybrid simulation, all the faults are assumed to be within the detailed systems. The buffer zone should include the areas where credible faults could potentially cause stalling of the A/C compressor motors in the study area.

5.2.1 Guide Regarding Transmission Bus Voltage Dip

To develop a guide to determine what transmission bus voltage dip will cause A/C motors in the underlying systems to stall, a generic subtransmission and distribution model as shown in Fig. 5.3 is considered. The total load is $20 + j10$ MVA. The 115/12.47 kV transformer reactance and the equivalent feeder impedance are specified on a 30 MVA base. A wide range of impedances between the source and end-use points, different A/C loading percentages (based on the ratio of the real power consumption of A/Cs to the real power of the total load) and typical A/C power levels have been considered. Voltage dips of different magnitudes, lasting 4 cycles were applied at Bus 1 and those that caused the
A/C motors connected to Bus 3 to stall were recorded. It can be observed from Fig. 5.4 that the smallest voltage dip magnitude causing A/C stall is larger than 0.25 pu. Thus, 0.75 pu can be adopted as the A/C stalling voltage threshold at a transmission bus. Accordingly, a voltage threshold of 0.75 pu was set as the voltage criterion in selecting buffer buses.

![Fig. 5.3 One-line diagram of a test system for determining the A/C motor stalling voltage tip at a transmission bus](image)

5.2.2 Boundary Identification

The study area includes the buses 24138 and 24151, together with the subtransmission and distribution systems that are supplied from them. A bus is included in the detailed
system if a single-phase or three-phase fault at that bus cause a phase-to-neutral voltage at buses 24151 and 24138 to fall below 0.75 pu.

Single-line-to-ground and three-phase faults at the 500 kV buses in this region are analyzed and the fault voltages at bus 24138 and bus 24151 are recorded and summarized in Table 5.2. Based on the short circuit voltages and the threshold of 0.75 pu, the area encircled by the dashed-dot line in Fig. 5.1 is chosen as the detailed system. It should be noted that a three-phase fault at bus 26105 causes the voltage of bus 24138 to fall below 0.75, nonetheless it is excluded from the detailed system, since it is relatively far from the load center of interest at bus 24151 and including it will significantly complicate the interface. A summary of the detailed system is provided in Table 5.3.

Table 5.2 The lowest phase voltage magnitude of the buses 24138 and 24151

<table>
<thead>
<tr>
<th>Faulted bus</th>
<th>bus 24151</th>
<th>bus 24138</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-phase fault</td>
<td>1-phase fault</td>
</tr>
<tr>
<td>24801</td>
<td>0.49</td>
<td>0.60</td>
</tr>
<tr>
<td>24092</td>
<td>0.60</td>
<td>0.71</td>
</tr>
<tr>
<td>24086</td>
<td>0.65</td>
<td>0.77</td>
</tr>
<tr>
<td>24236</td>
<td>0.69</td>
<td>0.78</td>
</tr>
<tr>
<td>15021</td>
<td>0.82</td>
<td>0.87</td>
</tr>
<tr>
<td>26105</td>
<td>0.83</td>
<td>0.91</td>
</tr>
<tr>
<td>24156</td>
<td>0.87</td>
<td>0.93</td>
</tr>
<tr>
<td>15093</td>
<td>0.87</td>
<td>0.92</td>
</tr>
<tr>
<td>24042</td>
<td>0.90</td>
<td>0.95</td>
</tr>
<tr>
<td>24097</td>
<td>0.99</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5.3 Initialization of the Detailed System

The first phase of the EMT simulation is to obtain a steady state initial condition. PSCAD initializes a system by ramping up the system from a zero initial condition to a steady state. In this study, the induction motor loads in the distribution systems served by
Table 5.3 Statistics of the detailed system model including subtransmission buses not shown in Fig. 5.1

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of buses</td>
<td>238</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of buses shown in Fig. 5.1</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of buses of different voltage levels (not shown in Fig. 5.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 kV</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>230 kV</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>161 kV</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>115 kV</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>92 kV</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;= 66 kV</td>
<td>105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Load</td>
<td>11.9 GW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

buses 24151 and 24138 account for more than 60% of the total load in terms of real power. At the induction motor starting stage, the induction motors draw a large amount of reactive power from the system. The bus voltages in the distribution system are significantly depressed to an extent that these induction motors, including the single-phase A/C induction motors, cannot be properly initialized. Consequently, with the default initialization procedure, PSCAD fails to properly initialize the detailed system.

To address this issue, a two-step initialization method is proposed, which is illustrated by the Fig. 5.5. A fixed voltage source whose magnitude and phase angle are set based on the power flow result of the reference planning model is used in the first step. For the first step, the switch $K$ for each load bus where a CLM is connected is turned to the position 0. The distribution systems and the CLMs are energized by the fixed voltage source and initialized independently. At the same time, the static equivalent load representing the distribution system is connected to the transmission bus and the transmission elements in the detailed system are initialized. After the CLMs are successfully initialized, the initialization process moves to the second step where the switch $K$ is turned to the position...
such that the detailed distribution system model is connected to the transmission system and replace the corresponding equivalent static load. Then the whole detailed system goes through a short-term adjustment process before finally reaching a steady state.

![Diagram](image)

Fig. 5.5 A schematic for illustrating the two-stage detailed system initialization process

5.4 Application of Hybrid Simulation to FIDVR Study on the WECC System

5.4.1 Benchmarking Hybrid Simulation against Transient Stability

The study case includes a detailed system consisting of 238 buses, 8 interface buses and an external system consisting of more than 15000 buses. To check whether the detailed system is correctly built in PSCAD and to test the accuracy and applicability of the hybrid simulation for a realistic large power system, the proposed hybrid simulation approach has been benchmarked against the positive sequence based TS simulation on the WECC system with all the loads represented by constant impedances.

The hybrid simulation starts at $t = 0$ s. A single line to ground (SLG) fault is applied on the phase A of bus 24151 at $t = 0.2$ s. Figs. 5.6-5.8 show the benchmark results. The
positive sequence voltages of buses 24151 and 24806 (one of the interface buses) are monitored and depicted in Figs. 5.6 and 5.7. The reactive power output of a machine at a large power plant at bus 15021 is also shown in Fig. 5.8. The results of the EMT-TS hybrid simulation and the TS simulation matched except for a small discrepancy in the post-fault

![Diagram of positive sequence voltage at bus 24151](image)

Fig. 5.6 The positive sequence voltage at bus 24151

![Diagram of positive sequence voltage at bus 24806](image)

Fig. 5.7 The positive sequence voltage at bus 24806
voltage recovery level at bus 24806 and a small time delay by the hybrid simulation. The delay is introduced by the positive sequence value extraction component of PSCAD.

5.4.2 FIDVR Study on the WECC System

(1) Distribution Network and Load Modeling

Equivalent models for the distribution networks and feeders are used to represent the distribution networks within the substation of bus 24151. The equivalent impedances of subtransmission systems are included in the models of the 115/12.5 kV transformers. The distribution feeders are modeled in two sections, i.e., the total load is divided into two portions. Two thirds of the total loads are connected at a quarter point along the feeder, with the rest one third of the load connected at the end of the feeder [46], as shown in Fig. 5.9. The parameters of the detailed A/C model are provided in Appendix A-4, with the scale being appropriately chosen to match the target percentage of total load. To model three-phase induction motors, a 20 horsepower, 380 V three-phase squirrel-cage induction...
motor has been used. The parameters of the motor are chosen to represent a typical NEMA type B induction motor. The driven mechanical torque is proportional to the square of its speed. Under-voltage motor protection is not modeled. A one-line diagram and data of the substation of bus 24151 are provided in the Fig. 5.10. Buses 24160 and 24229 are two 115 kV load-serving buses connected to bus 24151. The parameters and load models for all the equivalent feeders are assumed to be identical. Thus, the responses of A/Cs on one feeder will be used to illustrate the results in the following case studies.

(2) Propagation of A/C motor stalling to unfaulted phases

In this case, 75% of total load of the bus 24151 is assumed to be A/C load with the remaining load modeled by constant impedance loads. This case is referred to as case 1 hereafter. A single line to ground (SLG) fault is applied on the phase A of bus 24151 at 0.7 s (the corresponding fault point-on-wave is 0 degree), and cleared after 4 cycles.

The three phase voltages of the buses served by 500 kV bus 24151 are shown in Fig. 5.11. It can be observed that the SLG fault at bus 24151 depressed the phase voltages of both phases A and C at the distribution system level, due to the delta-wye connection of the 115 kV/12.47 kV step-down transformers.

The responses of the A/C motors connected at the quarter length point of a feeder are shown in Fig. 5.12. The terminal voltages of the A/C motors on all three phases drop when the fault is in effect, with the voltages on phases A and C being depressed down to around 0.4 pu. The terminal voltages of these two phases recover partially upon clearance of the fault. Consequently, the speeds of the A/C compressor motors on both phases A and C also recover. However, the level to which the voltages recover is lower than 0.6 pu. The speed recovery of A/C motors on both phases is not sustained under such a low voltage
Fig. 5.9 A two-section equivalent feeder model

Three-phase primary feeder: $Z_{feeder}^{(0)} = Z_{feeder}^{(1)} = 0.06 + j0.06 \text{pu}, Z_{feeder}^{(2)} = 2.5Z_{feeder}^{(1)}, \text{based on 12.47 kV, 250 MVA}$

Fig. 5.10 A detailed modeling of the substation of bus 24151
condition, and these motors start to stall at about 0.75 s. A/Cs on phase C stall at 0.9 s and A/Cs on phase A stall at 1.0 s. Subsequently, the terminal voltages of A/Cs on both phases are further depressed to about 0.4 pu.

The speeds of the A/C motors on phase B fully recover after the fault is cleared and sustain for 0.6 s. However, the voltage of phase B is also depressed due to the interaction with phases A and C through those 115/12.5 kV transformers. Further, reactive power consumption by the A/C motors on phase B increases as the terminal voltages decrease, as depicted in the Fig. 5.12, which, in turn, depresses the voltages further. These combined effects eventually lead to stalling of the A/C motors on phase B after 1.5 s.

As a result of the A/C stalling on all three-phases, three phase line-to-ground voltages of all the buses served by the substation of bus 24151 are significantly depressed, as shown in Fig. 5.13. Because the A/C motors on three phases stall at the different times, the three-phase voltages become significantly unbalanced after fault clearance until all A/Cs on three phases stall. The unbalance is clearly shown in both Fig. 5.13 and Fig. 5.14. After A/Cs on all three phases are stalled, the positive sequence voltage of the 115 kV bus 24160 is depressed down to 0.6 pu and the positive sequence voltage of the 500 kV bus 24151 is depressed down to 0.9 pu. During the simulation period, A/C motors remain in the stalled state, thus the voltages remain depressed. It can be expected that the transmission system voltage will only recover after the stalled A/Cs are tripped off.
Fig. 5.11 Three phase voltages at different locations served by the substation of bus 24151
Fig. 5.12 The responses of the A/C motors at the quarter length point of a feeder
Fig. 5.13 Three phase voltage magnitudes of buses served by the substation of bus 24151
Fig. 5.14 Three-sequence voltage magnitudes of three buses served by bus 24151
(3) *Effects of load composition on A/C motor stalling*

In this study, the effects of the load composition on A/C motor stalling and the occurrence of FIDVR events are simulated and analyzed. Five cases in total are examined as summarized in Table 5.4, with different percentages of single-phase A/C compressor motors, three-phase induction motors and constant impedance loads.

Table 5.4 Load composition data of the five study cases

<table>
<thead>
<tr>
<th>Case #</th>
<th>Load composition (in terms of real power)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75% 1-Φ A/C compressor motor, 25% constant impedance</td>
</tr>
<tr>
<td>2</td>
<td>75% 1-Φ A/C compressor motor, 10% 3-Φ NEMA type B induction motor, 15% constant impedance</td>
</tr>
<tr>
<td>3</td>
<td>70% 1-Φ A/C compressor motor, 15% 3-Φ NEMA type B induction motor, 15% constant impedance</td>
</tr>
<tr>
<td>4</td>
<td>60% 1-Φ A/C compressor motor, 15% 3-Φ NEMA type B induction motor, 25% constant impedance</td>
</tr>
<tr>
<td>5</td>
<td>50% 1-Φ A/C compressor motor, 25% 3-Φ NEMA type B induction motor, 25% constant impedance</td>
</tr>
</tbody>
</table>

It is observed from Fig. 5.15 that the SLG fault at bus 24151 eventually causes A/Cs on all three phases within the footprint of bus 24151 to stall for all the five study cases. These results indicate that propagation of A/C motor stalling to unfaulted phase is consistent across a substantial range of load compositions. The study implies that the impacts of SLG faults close to certain regions of the system with high A/C penetration could be more severe than perceived, and more attentions should be paid to them.

The major difference among the results is the time at which A/C compressor motor stalling occurs. An obvious trend is that less the A/C loads, the longer it takes for A/C compressor motors to start stalling. In case 2, 75% of the load is single-phase A/C motors.
Fig. 5.15 The speeds of A/C compressor motors at the 1/4 length point of the feeder f-1 served by bus 24160 for all five cases.
and 10% the load is three-phase induction motor. While in case 3, the corresponding percentages are 70% and 15%, respectively. Fig. 5.15 shows that it takes a longer time for A/Cs to stall in latter case than the former. The same trend is observed in the cases 4 and 5. These results confirm that three-phase induction motors are less onerous than the single-phase A/C compressor motor in terms of causing FIDVR problems. The reason is mainly twofold: first, less prone-to-stall A/C motors means less A/Cs will stall and less reactive power is drawn; second, during and immediately after the fault, three-phase induction motors actually support the system voltage by injecting VAr as they tend to keep their internal voltages constant during the fault period. This is apparent from the reactive power trace in Fig. 5.16.

Fig. 5.16 Power consumption of the three-phase induction motors at the 1/4 length point of an equivalent feeder within bus 24229 substation for case 3

(4) Effect of the point-on-wave (POW) characteristic of A/C compressor motor stalling
Research in [17] demonstrates that A/C compressor motor stalling is sensitive to the point on the voltage waveform when the fault is applied. How such a characteristic affects A/C motor stalling and the associated system dynamics with unsymmetrical faults in the transmission system is an important question to be answered. This question is answered through a comparison study as follows:

The case 5 discussed before is used here as the base case, and a SLG fault is applied at phase A of 500 kV bus 24151 \( t = 0.70 \) s with \( \text{POW} = 0 \) degree. A comparison case with the same SLG fault being applied at \( \text{POW} \) of 90 degrees, referred to as case 5A hereafter, is considered for this study. The fault is cleared after 4 cycles in both cases. As shown in the previous Fig. 5.15, A/Cs on three phases all stall in case 5. The A/C stalling results in a FIDVR event and delays the voltage recovery of local transmission and distribution buses as shown in the plots on the left of Fig. 5.18.

The responses of the A/Cs at the quarter length point of a feeder in case 5A are shown in Figure 5.17. It can be seen from the A/C motor speed plots in Fig. 5.17 that no A/C stalls in case 5A. The real power drawn by the A/Cs on three phases changes slightly even during the fault period. A/C motors contribute VAr support to the system during the fault period, but their reactive power consumption recovers back to the pre-fault level within a very short period after the fault is cleared. The current they draw during the period between fault clearance and voltage full recovery (at about 1.5 s) are larger than their rated values. As a result, their terminal voltage recovery is to some extent delayed. It takes about 0.7 s after the fault clearance for the terminal voltages to recover back to the pre-fault level. The corresponding impacts on the local transmission and distribution bus voltages are
shown in Fig. 5.18. The voltage recovery of these local buses is somehow delayed by the A/Cs.

The comparison results show that the POW effect leads to different results in terms of A/C stalling and the resulting system voltage recovery. Therefore, it is recommended that, for detailed FIDVR studies, the POW characteristic should be considered whenever possible, in order to obtain a clearer picture of potential outcomes as the POWs of actual faults in power systems are random.

![Fig. 5.17](image)

Fig. 5.17 The responses of the A/C motors at the quarter length point of a feeder with the fault POW as 90 degrees
Fig. 5.18 Comparisons of the bus voltages for two different POW cases: (left) case 5; (right) case 5A
(5) Computational performance

The experiment hybrid simulation platform set up in the laboratory consists of a desktop computer (processor: quad-core, 3.4 GHz, Intel Core i7-3770) and a laptop (processor: duo-core, 2.26 GHz, Intel Core P8400). Both are on the same LAN environment, connected via a wireless network with a speed of 250 Mb/s. PSCAD is installed and run on the desktop, while the developed three-sequence TS program is run on the laptop.

For a 3-second simulation of case 1, the computation times of different simulation approaches and interaction protocols are summarized in Table 5.5. The multi-core parallel computing capability of PSCAD (available since version 4.6) has been utilized in all the simulation methods. EMT-TS hybrid simulation results are reported in the first three rows. In the simulation done in the last row, the internal network is represented in detail but the external system is represented in a greatly simplified manner using a fixed Thévenin equivalent at the boundary buses. Correspondingly, the whole test case is simulated with PSCAD. Due to the large scale of the external system and utilization of multi-core parallel computing capability of PSCAD, the computational times used by the EMT and TS parts are comparable for this test case. In this context, compared to the serial protocol, the combined protocol reduces the computation time by 44%. The time difference between the combined and the serial protocols mainly corresponds to the time consumed by the TS part simulation and data exchange via the socket communication. Additionally, the computation time with the combined protocol is only marginally increased in comparison to that with the parallel protocol. Lastly, even compared with the pure EMT simulation of the detailed system, the computation time with the proposed hybrid simulation and the combined protocol is only
moderately increased. However, more accurate simulation results of the detailed system and the external system can be achieved using the hybrid simulation approach.

It should be noted that the advantage of the combined protocol over the serial protocol would become less significant in cases where either the EMT or TS part of the hybrid simulation dominates the simulation in terms of computation time.

Table 5.5 Performances of the hybrid simulation with different protocols

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>Computation time /s</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT-TS (parallel protocol)</td>
<td>371</td>
</tr>
<tr>
<td>EMT-TS (combined protocol)</td>
<td>387</td>
</tr>
<tr>
<td>EMT-TS (serial protocol)</td>
<td>692</td>
</tr>
<tr>
<td>EMT (the detailed system + a fixed equivalent of the external system)</td>
<td>264</td>
</tr>
</tbody>
</table>

5.5 Summary

The developed hybrid simulation platform is applied to the WECC system for a detailed FIDVR study of a region with a large percentage of single-phase A/C loads. The simulation results show that a normally cleared, single line to ground fault at a 500 kV bus close to the A/C loads can lead to a FIDVR event. The FIDVR event begins with A/Cs stalling on two directly impacted phases, followed by a propagation of A/C motor stalling to the A/C units on the unfaulted phase. Further, the effects of load composition are also investigated and five study cases with quite different load compositions show similar A/C motor stalling propagation phenomena. Last, the POW effects on the A/C stalling under unsymmetrical faults condition are also analyzed. The results indicate that the POW when the fault occurs could have a significant impact on the response of the A/C compressor motors and could influence whether or not a FIDVR event will occur.
CHAPTER 6
APPLICATION OF HYBRID SIMULATION TO POWER SYSTEMS INTER-FACED WITH HVDC SYSTEMS

6.1 Background

The power electronic converter technology has become one of the major enabling technologies for the evolution and development of power systems. In transmission systems, HVDC systems based on classical line current commutation (LCC) technology have been developed and installed around the world to deliver power over long distances or to connect two asynchronous power systems in a back-to-back manner [47]. In recent years, voltage source converter (VSC) HVDC technology has been increasingly adopted for integrating large-scale renewable energy into bulk power systems and connecting weak power systems [48]. FACTS devices have been installed in power systems to provide fast and flexible controls [49]. Furthermore, at present power electronic converters have been widely used in industrial motor drive systems and residential appliances [50], which suggests that the dynamic performance of the loads of power systems is considerably different from the loads in the past.

As the application of power electronic converter based devices increases, the dynamic performance and stability of power systems are increasingly influenced by the fast dynamics and non-linear behavior of these devices [51]-[52]. There are increasing concerns regarding the response of these power electronic converter based devices to a severe disturbance or fault that occurs close to their interconnection points, and the impact of these
power electronics based devices on the system. To address these concerns, the related phenomena need to be analyzed in a detailed yet systemic manner. The fast dynamics of the power electronic devices should be accurately simulated and simultaneously the slow dynamics of the systems need to be adequately captured.

Existing power system modeling and simulation practice approaches the fast switching transient and transient stability (slow dynamics) phenomena separately [1], since both have different time scales, as shown in the Fig. 6.1. This practice works well only when these two phenomena are not closely interrelated. However, the recent developments in power systems discussed above mean that both phenomena are interrelated and interact with each other, and time constants of the resulting transients range from microseconds to seconds. Therefore, a new approach is required for the future, which can handle fast switching transients and slow dynamic phenomena simultaneously in a practical and efficient manner. Before new practices and the supporting technologies become mature, the proposed hybrid simulation approach provides an effective solution, without changing the existing practices considerably.

Fig. 6.1 The time frame of power system dynamic phenomena [53]
The power electronic converter and its control technology are the fundamental building blocks for model power electronic devices. Two prevailing converter technologies are the LCC and VSC. The LCC technology is mainly used in the classical HVDC transmission, where the thyristor valve is used. VSC is regarded as a new generation converter technology, and it has been increasingly adopted in VSC-HVDC transmission systems and advanced FACTS devices [48].

The proposed hybrid simulation mainly addresses the issues of 3-phase modeling, phase imbalance and detailed A/C motor modeling and simulation in Chapter 5. In this chapter, the hybrid simulation will be utilized to solve the problem related to modeling power electronic converter based devices in power system dynamic simulations, as discussed before. In the following two sections, the proposed hybrid simulation will be applied to two different study cases: (a) a power system with a classical LCC-HVDC infeed and (b) a power system embedded with a VSC-HVDC. The hybrid simulation is conducted using the combined interaction protocol introduced in Chapter 3, by default, unless otherwise specified. Through these tests, the applicability of the hybrid simulation tool will be comprehensively evaluated for the two mainstream converter technologies.

6.2 Application to Power Systems Interfaced with a Classic HVDC System

In this section, the developed hybrid simulation platform is tested on the IEEE 39 bus system [54] with a classical LCC-HVDC link connected to bus 39, as shown in Fig. 6.2. The HVDC link is based on the CIGRE HVDC benchmark model [55], rated at 230 kV, 1000 MW, and shown in Fig. 6.3. In the hybrid simulation mode, the HVDC link is
modeled in PSCAD, with bus 39 as the boundary bus, while the remainder of the test system is simulated by the TS simulation. For benchmarking purpose, the whole test system is also modeled in PSCAD. The time step of the EMT simulation is 50 µs and the time step of the TS simulation is 5 ms.

Fig. 6.2 A modified IEEE 39 bus system with an HVDC link connected to bus 39

Fig. 6.3 The CIGRE HVDC benchmark model
The performance of the LCC-HVDC system is significantly influenced by the strength of the system at the point of interconnection. It is recommended that the short circuit ratio (SCR) should be at least 3.0 so that the HVDC system can achieve acceptable performance when subjected to severe disturbances [77]. In this test case, the SCR is 2.2. This means the connection point is weak for this HVDC infeed, which requires robustness of the hybrid simulation tool to handle such an unfavorable study case.

6.2.1 A 4-cycle, three-phase fault at bus 39

In this test case, a three-phase to ground fault is applied at bus 39, which is also the inverter AC bus, at 3.0 s and cleared in 4 cycles (0.0667 s). The benchmarking results are shown in Fig. 6.4 to Fig. 6.6. The results by both simulators overall are well matched, with a small discrepancy for a short period after the fault is cleared. The high frequency dynamics of the HVDC system over a short period after the fault is cleared is highlighted in Fig. 6.6(a). The results indicate that the hybrid simulation can adequately capture the high frequency behaviors of the HVDC model. It is shown in Fig. 6.6 that the dc voltage becomes negative during the period between 3.01 s and 3.03 s, which will be prevented in actual HVDC systems by the converter controls and/or protections. The main reason is that control scheme and settings in the model are not sophisticatedly optimized [55]. Actually, a similar result was also observed with the CIGRE HVDC test system and documented in [55]. Considering that the main objective of this comparison study to verify the accuracy of the developed tool, rather than the performance of the HVDC system, this HVDC model is acceptable for this study.
Fig. 6.4 Three-phase voltages of bus 39 (HVDC inverter AC bus)
Fig. 6.5 Three-phase current injection into the bus 39 from the HVDC inverter
The response of the external system is illustrated by the power of the generator at bus 30 shown in Fig. 6.7 and the positive sequence voltages at bus 1 and bus 9 shown in Fig. 6.8. The main discrepancy corresponds to the power oscillation during the fault period, which is mainly due to the difference in the modeling approaches between the two software packages. The other discrepancy corresponds to the oscillations observed in the real and reactive power output after the fault is cleared. The oscillation is of fundamental frequency, as shown in Fig. 6.9. It is found that the DC component in the stator current introduced by the fault clearing contributes to the oscillation. The DC component in the stator current is reflected as a fundamental frequency component in rotor, which results in fundamental
Fig. 6.7 Real and reactive power of the generator at bus 30

Fig. 6.8 Positive sequence bus voltages of the external system: (a) bus 1; (b) bus 9
Fig. 6.9 The DC components of three-phase current injection and the real power of the generator at bus 30

frequency oscillation in the generator power output. In the hybrid simulation, bus 30 is represented in the external system, where the DC component of the generator stator current cannot be represented by the phasor modeling approach. Thus, the oscillation cannot be captured by hybrid simulation mode.

Except for these two discrepancies, the overall impacts of the fault on the external system are adequately captured by the hybrid simulation approach. Considering the low SCR and the severity of the fault in this test case, the robustness of the developed hybrid simulation tool is also verified.
6.2.2 A 4-Cycle, Single-Line-to-Ground (SLG) Fault at Bus 39

(1) Simulation results

In this case, a single-line-to-ground (SLG) fault is applied at bus 39 at 3.0 s and cleared after 4 cycles. This test case is primarily intended to evaluate the developed tool under both fast dynamics and severely unbalanced conditions. In addition, the boundary selection flexibility introduced by the application of the three-phase/three-sequence network equivalents is analyzed by comparing the proposed equivalencing approach with the commonly used positive-sequence based equivalencing approach.

The hybrid simulation and pure EMT simulation benchmarking results are shown in Fig. 6.10 to Fig. 6.15. As the SLG fault is directly applied on the AC bus of the HVDC converter, the three phase voltages are severely unbalanced, as shown in Fig. 6.10. The waveforms of the three-phase current injections into the AC system at bus 39 from the HVDC inverter are also significantly distorted during the fault period, as shown in Fig. 6.12. The fast switching process of each valve of the bridge at the inverter, including a commutation failure occurring shortly after the fault is applied, is also captured by the hybrid simulation, as shown in Fig. 6.13. It can also be observed from the DC voltage and current shown in Fig. 6.13 that the hybrid simulation platform is capable of adequately simulating the high frequency dynamics of the HVDC system as well as the recovery process after the fault is cleared.

The power output of the generator at bus 30 is shown in Fig. 6.14. Fig. 6.15 shows the positive sequence voltages at bus 1 and bus 9. It can be seen that the dynamic response of the external system has been accurately simulated by the hybrid simulation.
The results presented above show that the proposed hybrid simulation method is accurate in comparison to the full-blown EMT simulation, under the phase imbalance and waveform distortion condition.

Fig. 6.10 Three-phase voltages of the AC bus of the HVDC inverter
Fig. 6.11 Three-phase current injection into bus 39 from the HVDC inverter
Fig. 6.12 Valve currents of the inverter
Fig. 6.13 DC voltage and current of the HVDC inverter: (a) DC voltage, (b) DC current

Fig. 6.14 Power output of the generator at bus 30
Fig. 6.15 Positive sequence bus voltages of the external system: (a) bus 1; (b) bus 9

(2) Performance

The performance of the hybrid simulation platform is compared with that of PSCAD by running this test case for a period of 5 s. It can be seen from Table 6.1 that the hybrid simulation is approximately 4.4 times faster than PSCAD.

Table 6.1 The performance of PSCAD and hybrid simulation for the IEEE 39 bus with a classic HVDC Link

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>Total simulation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT simulation using PSCAD</td>
<td>352 s</td>
</tr>
<tr>
<td>Hybrid simulation</td>
<td>81 s</td>
</tr>
</tbody>
</table>
Comparison with positive sequence TS simulation based hybrid simulation

To demonstrate the advantage of the proposed approach in terms of boundary selection, a comparison study is conducted against the conventional approach where the positive sequence based network equivalent and TS simulation are used. First, the system unbalanced condition during fault period is analyzed by simulating the whole test system in PSCAD and measuring the positive- and negative-sequence current flows throughout the system at the instant of 3.05 s (again the SLG fault is applied at 3.0 s and cleared at 3.0667 s). To quantify the current imbalance, an index $R_{im(i,j)}$ described by (6.1) is used. The result is tabulated in Table 6.2.

$$R_{im(i,j)} = \frac{i_{l,j}^{(2)}}{i_{l,j}^{(1)}}$$  \hspace{1cm} (6.1)

where $i_{l,j}^{(1)}$ and $i_{l,j}^{(2)}$ are the positive- and negative-sequence currents measured at the sending end of a branch connecting buses $i$ and $j$, respectively.

Suppose the positive sequence based network equivalent approach for hybrid simulation is used. Based on the unbalance condition shown in Table 6.2, if the imbalance index of 10% is chosen as the threshold for boundary selection, the boundary has to be extended to include buses 16, 19, 24 and 26 in the detailed system, which means at least additional 23 buses have to represented in the detailed system. In contrast to using only the bus 39 as the boundary bus with the proposed approach, such a boundary extension enlarges the scale of the detailed system extensively, which would definitely undermine the advantages of hybrid simulation. It can be envisioned that the extent of the resulting detailed system using the conventional approach could be even larger for a realistic large and meshed power system.

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Table 6.2 Branch current unbalance during a SLG fault

<table>
<thead>
<tr>
<th>Branch</th>
<th>From bus</th>
<th>To bus</th>
<th>Positive sequence current $I^{(2)}$ (A)</th>
<th>Negative sequence current $I^{(1)}$ (A)</th>
<th>Imbalance index $R_{im(i,j)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-9</td>
<td>8</td>
<td>9</td>
<td>726</td>
<td>563</td>
<td>0.78</td>
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<td>15-16</td>
<td>15</td>
<td>16</td>
<td>205</td>
<td>127</td>
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<td>7-8</td>
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<td>8</td>
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<tr>
<td>19-33</td>
<td>19</td>
<td>33</td>
<td>983</td>
<td>67</td>
<td>0.07</td>
</tr>
<tr>
<td>22-35</td>
<td>22</td>
<td>35</td>
<td>1059</td>
<td>69</td>
<td>0.07</td>
</tr>
<tr>
<td>20-34</td>
<td>20</td>
<td>34</td>
<td>861</td>
<td>52</td>
<td>0.06</td>
</tr>
<tr>
<td>12-13</td>
<td>12</td>
<td>13</td>
<td>232</td>
<td>9</td>
<td>0.04</td>
</tr>
</tbody>
</table>

6.3 Application to Power Systems Embedded with a VSC-HVDC System

There are two converter technologies for VSC-HVDC systems, i.e., high frequency pulse width modulation (PWM) control two-level or three-level type, and a more recent
modular multilevel converter (MMC) type [56]. This research focuses on the PWM control of two-level VSC-HVDC systems, as most of the commissioned VSC-HVDC projects use this type. The high switching frequency (in the range of 1000-2000 Hz) of the VSC-HVDC system poses a challenge to hybrid simulation, because a very small simulation time step has to be used in EMT simulation, and the resulting simulation time step ratio between EMT and TS become very large.

This test case is based on the IEEE 39 bus system, with a VSC-HVDC system added to connect the buses 8 and 29, as is shown in Fig. 6.16. The VSC-HVDC system is shown in Fig. 6.17. The constant active and reactive power controls are used in the rectifier, and a DC voltage control and an AC voltage control are employed in the inverter. The rated active power is 280 MW and the dc voltage is 400 kV.

The EMT simulation time step should be approximately one hundredth of the PWM carrier period to ensure good simulation precision. Hence, the EMT simulation time step is chosen as 5 µs, since the PWM carrier frequency of this VSC-HVDC system is 1980 Hz. The TS simulation time step is 5 ms.

The region encircled by the dashed line in Fig. 6.16 is the detailed system and modeled in PSCAD, with the rest of the AC system represented in three-sequence and simulated by the OpenHybridSim tool.
6.3.1 A 3-cycle, 3-phase to ground fault at bus 28

(1) Simulation results

A three-phase to ground fault is applied on bus 28 (one bus away from both the inverter AC bus and the boundary bus) at 1.0 s and it is cleared in 0.05 s (3 cycles). The
responses of the VSC-HVDC system to the fault, including DC and AC voltages and currents of the VSC-HVDC system and power output of the generator at bus 38 are presented in Fig. 6.18 to Fig. 6.23. The simulation result differences with reference to the EMT simulation are summarized in Table 6.3.

First, the results show that the hybrid simulation results are close to the reference simulation results obtained by PSCAD. The average differences of some key parameters monitored are less than 0.05 pu, as shown in Table 6.3.

Second, the main discrepancies appear in the first 6 cycles after the fault is cleared. In addition, the discrepancies are generally more apparent in the variables of the VSC-HVDC system, e.g., the DC voltage $V_{dc}$ and current $I_{dc}$, than those of the AC system. One factor contributing to the discrepancies is the harmonics and their impacts on the HVDC controls. The harmonics in the voltage and current at the inverter AC terminal are apparent during the fault period, as shown in the EMT simulation results in Fig. 18. However, high frequency characteristics of the external system are not adequately preserved in the equivalent used by the EMT-TS hybrid simulation. It is also observed that these discrepancies last for a very short period, thus they do not have a significant impact on the overall dynamics of the system. The simulation results obtained by the hybrid simulation and PSCAD simulation tend to “converge” again after 1.2 s.
Fig. 6.18 (a) Phase A current flowing into the VSC-HVDC system at bus 29 and (b) phase A voltage of bus 29
Fig. 6.19 Monitoring variables of VSC-HVDC rectifier: (a) real power, pu on VSC-HVDC system base; (b) reactive power flowing into the rectifier, pu on VSC-HVDC system base; (c) DC voltage; (d) DC current
Fig. 6.20  (a) Phase A current from the VSC-HVDC inverter into bus 8 and (b) phase A voltage of bus 8
Fig. 6.21 Monitoring variables of VSC-HVDC inverter: (a) real power, pu on VSC-HVDC system base; (b) reactive power flowing into the rectifier, pu on VSC-HVDC system base; (c) DC voltage
Fig. 6.22 Positive sequence voltage magnitudes of buses 29, 8 and 25

Fig. 6.23 Active and reactive power generation of the generator at bus 38
Table 6.3 The simulation result differences for the case of IEEE 39 bus system interfaced with a VSC-HVDC system (three-phase fault at bus 28)

<table>
<thead>
<tr>
<th></th>
<th>Average difference ((D_{avg})/pu)</th>
<th>Maximum difference ((D_{max})/pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_{dc}) of Rectifier</td>
<td>0.046</td>
<td>1.075</td>
</tr>
<tr>
<td>(V_{dc}) of Rectifier</td>
<td>0.007</td>
<td>0.042</td>
</tr>
<tr>
<td>(I_{abc}) of Rectifier</td>
<td>0.029</td>
<td>0.412</td>
</tr>
<tr>
<td>(V_{abc}) of bus 29</td>
<td>0.030</td>
<td>0.203</td>
</tr>
</tbody>
</table>

(2) The performance of hybrid simulation

With the simulation time step of EMT as 5 \(\mu\)s, and that of TS as 5 ms, the total simulation times of running the test system for a period of 2.0 s using PSCAD and the developed hybrid simulation tool, respectively, are summarized in Table 6.4. It shows that, for this study case, the performance of the developed EMT-TS hybrid simulation tool is approximately 7 times faster than the EMT simulation with PSCAD.

Table 6.4 Simulation performance comparison between hybrid simulation and EMT simulation for the case of IEEE 39 bus system embedded with a VSC-HVDC system

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>Time consumption (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT (with PSCAD)</td>
<td>1152</td>
</tr>
<tr>
<td>Hybrid simulation</td>
<td>164</td>
</tr>
</tbody>
</table>

6.3.2 A 3-cycle, single-line-to-ground fault at bus 29

A single-line-to-ground fault is applied at bus 29, which is the AC bus at the VSC-HVDC rectifier, at 1.0 s and cleared in 3 cycles. Simulation results are shown in Fig. 6.24-6.28. The simulation differences are summarized in Table 6.5. Compared to the simulation results in the previous test case, much less simulation differences are detected in this test case. The average simulation differences of the four variables shown in Table 6.5 are less than 0.02 pu.
The monitored variables, including real and reactive power flowing into the system and the DC voltage, in both the rectifier and inverter of the VSC-HVDC system are shown in Fig. 6.25 and Fig. 6.26, respectively. Double frequency oscillations in the power and DC voltages and currents are observed due to an unbalanced condition during the fault period. The oscillations are adequately simulated by the hybrid simulation. The impacts of the fault and the response of the external system is illustrated by the positive sequence voltage at
bus 25 (one bus away from the boundary bus 26) in Fig. 6.27, and it is accurately captured by the proposed hybrid simulation.

Fig. 6.25 Monitored variables of the VSC-HVDC rectifier
Fig. 6.26 Monitored variables of the VSC-HVDC inverter
Fig. 6.27 Positive sequence voltage of bus 25

Table 6.5 The simulation result differences for the case of IEEE 39 bus system embedded with a VSC-HVDC system (SLG fault at bus 29)

<table>
<thead>
<tr>
<th></th>
<th>Average difference ($D_{avg}$)/pu</th>
<th>Maximum difference ($D_{max}$)/pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{dc}$ of rectifier</td>
<td>0.010</td>
<td>0.084</td>
</tr>
<tr>
<td>$V_{dc}$ of rectifier</td>
<td>5.3E-4</td>
<td>0.004</td>
</tr>
<tr>
<td>$I_{abc}$ of rectifier</td>
<td>0.012</td>
<td>0.159</td>
</tr>
<tr>
<td>$V_{abc}$ of bus 29</td>
<td>0.011</td>
<td>0.072</td>
</tr>
</tbody>
</table>

6.4 Summary

The developed hybrid simulation tool is applied to power systems interfaced with two typical HVDC systems: (1) the classical HVDC system (2) the VSC-HVDC system.

Based on the results of classical HVDC test system, it is observed that the selection of the converter interface buses as the boundary bus for hybrid simulation can achieve a reasonably good accuracy with the proposed hybrid simulation approach. In addition, a comparison study shows that a smaller extent of the detailed system is required by the
proposed hybrid simulation approach than the previous hybrid simulation approaches under an unsymmetrical fault condition.

The developed tool is also applied to the IEEE 39 bus system embedded with a VSC-HVDC link. Two important scenarios, including a severe three-phase fault and an unsymmetrical fault close to the VSC-HVDC rectifier station, have been considered in the two test cases. In both test cases, the proposed hybrid simulation approach produces simulation results close to that obtained by simulating the whole system in PSCAD. More importantly, compared to all EMT simulation, more than 85% computation time saving is achieved by the proposed approach in this test case.
CHAPTER 7
INTEGRATED TRANSMISSION AND DISTRIBUTION SYSTEM MODELING AND SIMULATION

Distribution systems increasingly influence the behavior of bulk power systems, as a result of nonlinear characteristics of the loads and distributed generation resources. The interactions between distribution and transmission systems have also increased. However, in traditional power system simulation tools, transmission and distribution systems are separately modeled and analyzed. Hence, it is difficult to analyze the impacts of distribution systems on transmission systems in detail and vice versa. Admittedly, the hybrid simulation approach can be applied to analyze integrated transmission and distribution (T&D) systems, with the distribution systems being simulated by the EMT simulator. However, the hybrid simulation approach is not well suited for the cases with tens to hundreds of complex distribution systems interfaced with the transmission system.

A phasor modeling based integrated simulation approach is proposed to address the demand. An integrated modeling framework is first developed in this chapter, where the transmission system is modeled as one subsystem in three-sequence detail, while each distribution system is represented as a subsystem and modeled in three-phase detail. The integrated T&D power flow (TDPF) is solved by iteratively solving a three-sequence power flow for the transmission system and a three-phase power flow for each distribution system. For the integrated T&D dynamic simulation (TDDS), the main challenge is associated with different network representations in the transmission and the distribution systems. With the partitioned solution approach adopted in the TDDS algorithm, the multi-area Thévenin
equivalent (MATE) approach is utilized in the network solution step to address this challenge.

7.1 Integrated Transmission and Distribution System Modeling

In deciding an appropriate modeling approach for integrated transmission and distribution systems, the following two important factors have to be considered: (1) the physical features of transmission and distribution systems; (2) the common modeling assumptions that could be made for both power flow and dynamic simulation.

Firstly, distribution systems generally should be modeled in three-phase detail for both power flow and dynamic simulation, as distribution systems are inherently unbalanced. Secondly, the conditions at the boundary between the transmission and distribution systems are influenced by the unbalanced conditions of the distribution systems and the fault(s) considered in dynamic simulation. Therefore, although transmission systems can be assumed to be physically three-phase balanced, the typical assumption that the boundary conditions at the interfaces between transmission and distribution systems are reasonably balanced is not always valid, particularly in dynamic simulation. In this context, the transmission system should be represented in either three-sequence or three-phase detail. To avoid the modeling and computational complexity involved in three-phase representation and to effectively reuse the existing sequence component-based models and simulation algorithms, the transmission system is modeled in three-sequence in this research.
7.2 Power Flow Algorithm for Integrated Transmission and Distribution System

The proposed TDPF algorithm is formulated based on a master-slave approach [57], with the power flow of the transmission system as the master problem and the power flow of the distribution systems as the slave problem. The main differences from [57] include: 1) modeling the transmission system in three-sequence instead of positive sequence; 2) a three-sequence power flow algorithm is developed for the transmission system; 3) appropriate three-sequence representations of the distribution systems in the power flow formulation of the transmission system.

The boundary information exchanged between the transmission and the distribution systems during the integrated power flow solving process is illustrated in Fig. 7.1. At each iteration between the transmission and the distribution systems, the transmission system provides the three-phase voltages at the boundary buses, denoted by $V_{Bi}^{abc}$, to the corresponding distribution systems to update their boundary (source) bus voltages. Similarly, the results from the distribution systems are transformed to three sequence equivalents. The positive sequence component is represented by a constant power load $LoadPQ_i^{(1)}$ as in a conventional balance power flow. The negative- and zero-sequence components are represented by negative sequence current injection $lnj_i^{(2)}$ and zero sequence current injection $lnj_i^{(0)}$, respectively at the appropriate boundary buses.
Fig. 7.1 Boundary data exchange between the transmission and the distribution systems in the integrated power flow

In the transmission system part, the three sequence networks are decoupled and solved independently. The positive sequence network is solved using existing positive sequence power flow algorithms. The negative- and zero-sequence networks are represented by (7.1) and (7.2).

\[ I^{(2)} = Y^{(2)} V^{(2)} \]  
(7.1)

\[ I^{(0)} = Y^{(0)} V^{(0)} \]  
(7.2)

Superscripts 2 and 0 denote negative- and zero-sequence components, respectively. The negative- and zero-sequence bus current injections in \( I^{(2)} \) and \( I^{(0)} \) are zero except for the boundary buses when they are interfaced with unbalanced distribution systems. \( V^{(s)} \) is the sequence bus voltage vector; \( Y^{(s)} \) is the sequence admittance matrix of the network.

A sequence network solver for solving (7.1) and (7.2) has been developed based on the short circuit program in InterPSS. The sequence admittance matrices are fixed unless
there is a network change. They are factorized at the initialization stage, and (7.1) and (7.2) are solved only once for each transmission system power flow. Thus, the computational burden due to the solution of (7.1) and (7.2) is marginal.

For the distribution systems, a three-phase power flow based on the backward/forward sweep (BFS) algorithm [46] has been developed. The flowchart of the integrated power flow algorithm is shown in Fig. 7.2.

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**Fig. 7.2** The flowchart of the integrated T&D power flow
7.3 Dynamic Simulation for Integrated Transmission and Distribution System

7.3.1 Formulation and Solution of Dynamic Simulation

The dynamic simulation of power systems can be mathematically described as a solution to a set of differential-algebraic equations (DAEs) as follows [79]:

\[ \dot{x} = f(x, V) \]  \hspace{1cm} (7.3)

\[ I(x, V) = YV \]  \hspace{1cm} (7.4)

with a set of known initial conditions \((x_0, V_0)\), where \(x\) is a vector of the state variables; \(V\) is the bus voltage vector; \(I\) is the bus current injection vector; \(Y\) is the nodal admittance matrix of the network. Conventionally \(V, I\) and \(Y\) represent the positive sequence only. In the following sections, they will be extended to three-sequence and three-phase reference frameworks.

Based on the way in which (7.3) and (7.4) are interfaced with each other, there are basically two solution approaches for the above DAEs, i.e., a simultaneous approach and a partitioned approach [79]. In the simultaneous solution approach, (7.3) is first converted to a set of algebraic equations, which are lumped with (7.4) to form a single larger algebraic equation set. It is complicated to formulate the equation sets with different network representations for the transmission and the distribution systems. On the other hand, with the partitioned solution approach, the differential equation set (7.3) and the algebraic set (7.4) are solved separately. The corresponding solution processes are generally referred to as the integration step and the network solution step, respectively. Such a decoupling feature allows the integration method and the network solution method to be chosen independently and facilities the solution of integrated transmission and distribution systems.
Based on the discussions above, the partitioned solution approach is adopted for integrated transmission and distribution dynamic simulation. For the integration step, dynamic models basically require some local measurements (for example, bus voltage and frequency at the terminal or an associated remote control bus) to perform the integration. Furthermore, the transmission and the distribution systems are represented as individual subsystems based on the proposed modeling framework. Thus, appropriate integration algorithms can be reused or developed for the transmission and the distribution systems independently. Compared to existing dynamic simulation algorithms for bulk power systems [79], no special change is required in the integration step for the integrated transmission and distribution systems.

On the other hand, almost all the existing simulation programs require the same representation (either single-phase or three-phase) for the whole system to build the network admittance matrix for solving network solution. Considering the different representations in the proposed modeling approach, the single-network oriented network solution approach cannot be directly applied to the integrated transmission and distribution systems. Therefore, a special network solution approach, which is capable of accommodating multiple subsystems and distinct network representation of each subsystem, is needed at the network solution step. In this following section, a diakoptics [69] based network solution approach will be utilized to address this issue.
7.3.2 Diakoptics and Multi-area Thévenin Equivalent

One important benefit of the concept of diakoptics is that the individuality of the resulting subsystems is maintained, which allows these subsystems to be modeled and simulated distinctly. The original diakoptics based solution proposed by Happ [69], which was based on the concept of “open and closed path contours”, was difficult to visualize and formulate in a clear and straightforward manner [67]. In addition, the solution cannot be directly applied to the cases where the subsystems are not modeled at the same level of detail. The multi-area Thévenin equivalent (MATE) concept is developed based on the diakoptics concept and the formulation of modified nodal analysis (MNA)[70]. MATE re-formulates and extends the diakoptics approach to make it easier to understand and program into an algorithm.

A detailed derivation and formulation of the MATE based algorithm can be found in the Appendix-B. The MATE approach based network solution for a system consisting of multiple subsystems includes four steps, as illustrated in Fig. 7.3:

1. Solve each subsystem network without current injections from the link branch(es) to obtain the bus voltages $V_{int,i}$.

2. Retrieve boundary bus voltages from $V_{int,i}$ and build the subsystem network Thévenin equivalents, as illustrated in the dashed rectangular part in Fig. 7.3(c).

3. Build the link subsystem by connecting the Thévenin equivalents with the link branches, and then solve it to obtain the currents of the link branches, as shown in Fig. 7.3(c).
(4) Solve each subsystem network again considering only the link branch current injection(s) to obtain the solution $V_{ext,i}$, as shown in Fig. 7.3(d). Based on the superposition theorem, the final bus voltages are obtained by $V_{sub,i} = V_{int,i} + V_{ext,i}$.

The MATE approach can be used to reconcile the individual solutions of subsystems into a full-system simultaneous solution at the network solution stage. When non-linear models exist in the system, iterations of the solution process above are required. For integrated T&D systems, this reconciliation process is illustrated in Fig. 7.4. The transmission system and the distribution systems can be first solved independently with their own...
representations and solution techniques. Then the interactions among them can be reconciled at the level of the link branches by sharing their Thévenin equivalents and solving the resulting link subsystem. Considering different representations, a reference coordinate system and necessary coordinate transformations are required at the coordination stage, which will be discussed in more detail in Section 7.4.

Fig. 7.4 Coordination of the subsystem simulation solutions through the link subsystem using the MATE approach

7.3.3 Development of Three-Phase Dynamic Simulation Algorithm

The three-sequence transient stability simulation algorithm developed in Chapter 4 can be used to simulate the transmission system. For the distribution systems, a three-phase dynamic simulation algorithm needs to be developed. The overall simulation procedure of three-phase dynamic simulation is similar to the existing positive sequence dynamic simulation. The main differences are associated with three-phase oriented network representation and dynamic modeling. One of the important objectives in this development process is that well-tested three-sequence based models are re-used and formidable re-programming efforts are avoided whenever possible. This objective is mainly achieved through
applying the inheritance feature of object-oriented programming and the adapter design pattern [71] throughout the development.

(1) Modeling of three-phase components

The mapping relationship between three-sequence and three-phase modeling are shown in Fig. 7.5. Static components, such as transmission lines, transformers, static loads (impedances and admittances) can be directly transformed from three-sequence representations to three-phase representations. Existing three-sequence parameters can be used as input, and transformed to the corresponding three-phase values internally.

In the model transformation, three-phase transformers deserve special attention because the transformation is affected by the type of connection of their windings [72]. Typical transformer connections, such as wye grounded-wye grounded, delta-wye grounded, delta-delta, have been considered in this development.

![Three-phase modeling diagram](image)

Fig. 7.5 Transformation from three-sequence modeling to three-phase modeling
For three-phase rotating machines, their structure and operation characteristics have been considered in developing their three-phase dynamic models. Firstly, their dynamics are mainly determined by the positive sequence components [1],[73],[74], due to the inherent symmetric structure of the rotating machines and the way they are connected to the system. Secondly, when interfaced with a three-phase network, they can be represented as a three-phase Norton equivalent as shown in Fig. 7.6. In addition, due to the internal symmetric structure of the machines, the internal three-phase current injection $I_{gen}^{abc}$ shown in Fig. 7.6 is always balanced, and corresponds to the current injection in the positive sequence based model. $I_{gen}^{abc}$ is dependent on the internal state variables and updated at each TS simulation time step, while the three-phase Norton admittance $Y_{gen}^{abc}$ is transformed from the three-sequence machine admittances and kept constant during the simulation. With these features taken into account, the existing three-sequence based machine modeling of the three-phase rotating machines can be reused for three-phase TS simulation through the adapter design pattern, which is illustrated by the “wrapper” frame over the existing three-sequence based machine models in Fig. 7.5.

Fig. 7.6 A Norton equivalent model of the three-phase machine (both synchronous and induction machines) for three-phase TS simulation
The actual implementation of the three-phase machine model is illustrated in Fig. 7.7. The main function of the machine adapter is to invoke the functions of the existing positive sequence model to update the state variables through an integration step and then calculate the positive sequence current source, which is subsequently transformed to the three-phase current source $I_{gen}^{abc}$ and used later in the three-phase oriented network solution.

![Diagram](image)

**Fig. 7.7** Implementation of three-phase machine model based on the corresponding three-sequence model using adapter pattern

**2) Modeling of single-phase components**

Static single-phase components, such as single-phase secondary distribution feeder, impedances and admittances, can be modeled in a manner similar to the positive sequence modeling. In dynamic simulation, they are directly added to the network admittance matrix. As for single-phase dynamic components, such as single-phase residential air conditioners, a single-phase Norton equivalent model can be used to interface with the network. The equivalent current source should be updated at each step based on the dynamic response of the component to the boundary bus condition, while the equivalent admittance should be
fixed during the simulation. A dynamic model of single-phase air-conditioner has been developed with this modeling approach. The dynamic performance of this model is based on the A/C performance model proposed by WECC [22], [80], which has two operating states, i.e., run and stall, and the corresponding characteristics are shown in Fig. 7.8. In this research, this model is developed in a single-phase oriented framework, instead of the original positive-sequence representation. This model will be used in the test cases in this chapter and the Chapter 8.

![Fig. 7.8 The power consumption versus terminal voltage characteristics of the A/C compressor motor under the “run” and “stall” operation conditions [80]](image)

7.3.4 MATE-based Three-Phase/Three-Sequence Dynamic Simulation Algorithm

The three sequence TS simulation, the three-phase dynamic simulation combined with the MATE approach together form the TDDS algorithm. The key steps of the TDDS algorithm are shown in Fig. 7.9. During the implementation, several key issues have been identified and addressed:
For the proposed power flow algorithm, a common boundary bus shared by the transmission system and a distribution system is required. On the other hand, for the dynamic simulation, the subsystems should be connected through branches, as illustrated in Fig. 7.9.
Fig. 7.3(a), in order to comply with the formulation of the MATE approach. To facilitate the same subsystem model being used for both power flow and dynamic simulation, the subsystems are split based on the bus splitting concept and connected by “virtual” breakers. For each boundary bus, a dummy bus is created during the network partition stage. Subsequently, a “virtual breaker” (represented by a branch with a small impedance, i.e., 0.0001 pu) is introduced to connect them. At the simulation stage, the virtual breakers connecting the transmission and the distribution subsystems are “switched off” and not used in power flow, but “switched on” for the integrated dynamic simulation. The virtual breakers become the link branches in MATE based dynamic co-simulation.

(2) While the transmission system is modeled and solved as one subsystem in power flow, it is not necessarily represented as one subsystem for dynamic simulation. It can also be further split into subsystems and the resulting subsystems can be represented either in three-sequence or three-phase, depending on the application requirements. Such splitting is useful for analyzing unbalanced faults in the transmission system and realizing parallel dynamic simulation.

(3) A common (reference) coordinate system should be predefined and used for coordinating different representations of transmission and distribution systems. In the present implementation, the three-sequence coordinate is chosen as the default common coordinate. For the subsystem(s) modeled in three-phase detail, the following data processing is required: (a) the three-phase Thévenin equivalent is built first, and transformed to the three-sequence Thévenin equivalent; (b) after the three-sequence currents of the link
branches are obtained from the link subsystem solution results, they need to be converted to three-phase.

(4) Unbalanced faults are processed in a special manner. A basic requirement of building a three-sequence Thévenin impedance matrix for a subsystem modeled in three-sequence representation is that three sequence networks of the subsystem are decoupled. If an unbalanced fault were applied to a subsystem modeled in three-sequence representation, the three sequence networks would become coupled at the fault point, which violates the requirement. Therefore, if an unbalanced fault is applied in the transmission system, the corresponding portion of the transmission system should be represented as one subsystem modeled in three-phase detail. However, it should be emphasized that the size of this three-phase modeling portion can be as small as only including the faulted bus. Therefore, the advantage of three-sequence modeling can be preserved.

(5) Both the coordinate systems (three-phase or three-sequence) and network (transmission or distribution) attributes are added to the subsystems. As the solution methods for three-phase and three-sequence coordinates are different, so also are the solution methods for transmission and distribution systems. The coordinate and network attributes added to the subsystems can help identify an appropriate simulation algorithm for each subsystem during simulation.

7.3.5 Potential Applications

Besides the transmission and distribution system integrated dynamic simulation discussed earlier, there are other potential applications of the developed three-phase/three-sequence dynamic simulation algorithm, such as:
• This multi-area modeling and dynamic simulation approach can be combined with the developed EMT-TS hybrid simulation to realize simulation mode switching from EMT-TS hybrid simulation to TS simulation, which will be discussed in the next chapter.

• Dynamic simulation considering multiple simultaneous faults, with the portion of the system, where multiple simultaneous faults occur, modeled in three-phase detail

• Impact study on power systems of high penetration level of distributed generation in distribution systems

• Research on distributed control at the distribution system level to provide support (e.g., voltage and damping) to bulk power systems

7.4 Test cases

A simple 8-bus distribution feeder shown in Fig. 7.10 is used to build the distribution systems. The total load on the feeder is 8 MW. The feeder consists of 7 sections of non-perfectly transposed overhead lines. The line codes and parameters are based on the IEEE 13-bus test feeder [81]. There are 7 equivalent loads, and their parameters are shown in Fig. 7.10. The loads are wye-connected and are identical on the three phases, unless otherwise specified in the test cases.

Fig. 7.10 A simple 8-bus distribution feeder
In the following test cases, the IEEE 9 bus and 39 bus test systems are used to represent the transmission system. In creating the integrated T&D systems, the distributed system shown in Fig. 7.10 is used to replace the original aggregated loads connected at the transmission buses. In addition, the feeder model and loads are scaled to match the original load seen by the transmission system. In the test case involving the IEEE 9 bus system, the loads served by buses 5, 6 and 8 are replaced by the distribution systems. The resulting integrated system is referred to as T9D3. In the test case involving the IEEE 39 bus system, the loads served by buses 15, 16, 18, 26, 27 and 28 are replaced by the distribution systems, and the resulting integrated system is referred to as T39D6 hereafter. The corresponding portion of the system is shown in Fig. 7.11.

Fig. 7.11 A portion of the IEEE 39 bus system

The 69 kV subtransmission buses (corresponding to the Bus 0 in Fig. 7.10) are selected as the interface between the transmission and the distribution systems. The number of a distribution bus in the integrated system is defined based on (7.5):

\[ N_{\text{dist},i}^{\text{new}} = 10N_{\text{tran},i} + N_{\text{dist},i}^{\text{old}} \]  

(7.5)
\( N_{\text{dist},i}^{\text{new}} \) denotes the new bus number of distribution bus \( i \); \( N_{\text{tran},i} \) is the number of the transmission bus to which the associated distribution system of bus \( i \) is connected; \( N_{\text{dist},i}^{\text{old}} \) is the original bus number of distribution bus \( i \) used in Fig. 7.10.

To consider load unbalance condition, a loading unbalance factor \( \beta \) is defined. Loads on the three phases are defined as:

\[
P_{L,i}^A = \frac{1}{3} P_{\text{Total},i}, \quad P_{L,i}^B = \frac{1-\beta}{3} P_{\text{Total},i}, \quad P_{L,i}^C = \frac{1+\beta}{3} P_{\text{Total},i}
\]

(7.6)

where \( P_{L,i}^A, P_{L,i}^B \) and \( P_{L,i}^C \) are the real part of load on phase \( A, B \) and \( C \) of bus \( i \), respectively, and \( P_{\text{Total},i} \) is the sum of them.

7.4.1 The Integrated T&D Power Flow Algorithm

(1) Verification by Comparing with PSCAD

There is no publically available phasor domain simulation program capable of modeling and simulating integrated T&D systems that can be used for comparison. Electromagnetic transient simulation programs support modeling and simulating integrated T&D systems in three-phase, point-on-wave detail. Hence, the proposed integrated T&D power flow algorithm is benchmarked against PSCAD. The T9D3 test case is used for benchmarking purposes. The comparison results are shown in Table 7.1 and Table 7.2. The positive sequence bus voltages are extracted from their corresponding voltage waveforms using the FFT component in PSCAD. It can be observed that the both the transmission and distribution power flow results obtained from the proposed TDPF algorithm closely match with those of PSCAD.
Table 7.1 Positive sequence voltages of the buses in the transmission system

<table>
<thead>
<tr>
<th>bus</th>
<th>magnitude (pu)</th>
<th>angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TDPF</td>
<td>PSCAD</td>
</tr>
<tr>
<td>4</td>
<td>1.028</td>
<td>1.028</td>
</tr>
<tr>
<td>5</td>
<td>1.002</td>
<td>1.001</td>
</tr>
<tr>
<td>6</td>
<td>1.014</td>
<td>1.013</td>
</tr>
<tr>
<td>7</td>
<td>1.028</td>
<td>1.027</td>
</tr>
<tr>
<td>8</td>
<td>1.018</td>
<td>1.017</td>
</tr>
<tr>
<td>9</td>
<td>1.033</td>
<td>1.033</td>
</tr>
</tbody>
</table>

Table 7.2 Three phase voltages of some selected buses in the distribution system served by bus 5

<table>
<thead>
<tr>
<th>bus</th>
<th>phase</th>
<th>magnitude (pu)</th>
<th>angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TDPF</td>
<td>PSCAD</td>
</tr>
<tr>
<td>51</td>
<td>A</td>
<td>1.007</td>
<td>1.009</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1.009</td>
<td>1.011</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1.007</td>
<td>1.010</td>
</tr>
<tr>
<td>55</td>
<td>A</td>
<td>0.967</td>
<td>0.967</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.981</td>
<td>0.984</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.964</td>
<td>0.967</td>
</tr>
<tr>
<td>58</td>
<td>A</td>
<td>0.947</td>
<td>0.945</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0.960</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.935</td>
<td>0.940</td>
</tr>
</tbody>
</table>

(2) Robustness of the proposed algorithm under different levels of load unbalance

As shown in Table 7.3, the integrated T&D power flow iteration counts for both test cases are insensitive to the load unbalance conditions in the distribution systems, which indicates the robustness of the proposed algorithm.
Table 7.3 Number of iterations in the integrated T&D power flow under different load unbalance conditions

<table>
<thead>
<tr>
<th>Test case</th>
<th>Scenario</th>
<th>Number of iterations (k in Fig. 7.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T9D3</strong>  (IEEE 9 bus system interfaced with 3 distribution systems)</td>
<td>Base case</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5% load unbalance</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>10% load unbalance</td>
<td>3</td>
</tr>
<tr>
<td><strong>T39D6</strong> (IEEE 39 bus system interfaced with 6 distribution systems)</td>
<td>Base case</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5% load unbalance</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>10% load unbalance</td>
<td>3</td>
</tr>
</tbody>
</table>

7.4.2 *The Integrated T&D Dynamic Simulation Algorithm*

The proposed TDDS algorithm has been tested on the T9D3 system. In dynamic simulation, all loads are represented by constant impedances. The whole system has also been modeled and simulated in PSCAD. At 1.0 s, a single-line-to-ground (SLG) fault is applied at the 69 kV bus 50 of the distribution system served by bus 5, and cleared after 0.07 s. The three-phase voltages of bus 52 in the distribution system is shown in Fig. 7.12, and the three-sequence voltages of bus 5 is shown in Fig. 7.13. It can be seen from both results that, other than the 1-cycle time delay introduced in extracting the fundamental frequency components using the FFT component in PSCAD, the simulation results of TDDS match well with those of PSCAD.
Fig. 7.12 Three phase voltages of bus 52 in the distribution system served by bus 5

Fig. 7.13 Three-sequence voltages of bus 5 in the transmission system
7.5 Application to FIDVR Study Under Unbalanced Conditions

The FIDVR problem has been mainly studied using the composite load model and positive-sequence TS simulation programs [22]. It is pointed out in [22] this modeling and simulation approach is not applicable to unbalanced fault conditions. In addition, an aggregation approach has been used to build the composite load model. All motors in a feeder are assumed to have the same running and stall characteristics, and they stall at the same time. Considering their location differences as well as the resulting A/C stall time and trip time differences, the assumption could result in simulation results significantly different from their actual responses. These issues can be addressed by the proposed integrated T&D modeling and simulation approach. The following two study cases are conducted on the T39D6 system. In the base case, the three-phase loads are assumed to be balanced. The load composition is 50% single-phase residential A/C motor combined with 50% constant impedances. The default parameters of the A/C performance model provided in PSLF user manual are used in the studies, except that the stalling voltage threshold is set to 0.65 pu. The stalling time is 0.033 s. The full parameter list is provided in Appendix A-5.

(1) A FIDVR Event Triggered by a SLG Fault in The Transmission System

In this test case, bus 17 and the connected branches in the transmission system are modeled as a subsystem in three-phase detail during dynamic simulation to accommodate an unbalanced fault. A SLG fault is applied on phase A of bus 17 at 1.0 s and cleared after 0.07 s. Due to the delta-wye connection of the distribution transformers, phases A and B at the distribution systems are directly affected by the fault. The phase A voltages of the buses at the end of the feeders are shown in Fig. 7.14. It can be observed that the SLG fault causes
stalling of A/Cs on phase A in the distribution systems served by buses 15, 16, 18 and 27, but there is no A/C stalling within the distribution systems served by buses 26 and 28, as both are relatively far away from the fault. Phase A voltages start to recover at around 5 s as A/C motors are gradually tripped off by their thermal protections.

![Fig. 7.14 Phase A voltages of the buses at the end of the feeders](image)

The phase A voltages of the distribution feeder buses served by bus 15 are shown in Fig. 7.15. The voltage profiles of the buses at different locations within one distribution system are significantly different. As shown in the Fig. 7.16, in this FIDVR event, only the A/Cs connected at bus 154 and the buses downstream of bus 154 stall, while those connected to the upstream buses (i.e., buses 152 and 153) do not stall. Such diverse responses of A/Cs in the same distribution system have not been properly represented in the existing
composite load model [22], where all A/Cs served by the same substation are assumed to respond identically to the fault. It can be expected that similar detailed studies can provide valuable references to further improve the composite load models, particularly the aggregation of A/Cs considering the different responses.

![Fig. 7.15 Phase A voltage of feeder buses served by bus 15](Image)

On phase B, only the A/Cs connected to the bus at the end of the feeder served by bus 18 stall, the A/Cs on phase B of the upper stream buses of the same distribution system and within other distribution systems do not stall. Although phase C is not directly affected by the fault, the impacts of the FIDVR event on phase C of buses within each distribution system are obvious, as illustrated in Fig. 7.17. The impacts are mainly due to the three-phase interactions through the delta-wye connection of the distribution transformers.
Fig. 7.16 The operation status of the A/C motors connected to phase A of the buses along a feeder served by bus 15 (status = 1 means running, status = 0 means stall and status = -1 means being tripped off)
The impact of the FIDVR event on the transmission system is shown in Fig. 7.18, which are the positive and negative sequence voltages of buses 15, 27 and 28. The results show that the load unbalance in the distribution systems during the event results in noticeable voltage unbalance in the transmission system, indicated by the negative sequence voltages. Zero sequence voltages only appear in transmission system during the fault period, thus they are not included in Fig. 7.18.

(2) Impacts of load unbalance and composition unbalance

In the following study, the load unbalance factor \( \beta \) is set to be 5%. The load composition unbalance is considered by changing the A/C load composition on phases A and C by 5%, namely, the percentages of single-phase A/C motors on phases A, B and C become 45%, 50% and 55%, respectively. Correspondingly, the percentages of impedance loads on three phases are changed to 55%, 50% and 45%, respectively. Two scenarios have been studied: 1) only load unbalance; 2) both load unbalance and composition unbalance.
Fig. 7.18 Sequence voltages of transmission buses 15, 27 and 28: (a) positive sequence; (b) negative sequence

A three-phase fault is applied at bus 3 at 1.0 s and cleared after 0.07 s. The three-phase voltages of bus 158 (at the end of a feeder) are shown in Fig. 7.19. The three phase voltages of bus 150 (an interface bus between transmission and distribution) are shown in Fig. 7.20. Although the fault is a three-phase fault, the load unbalance and load composition unbalance result in different voltage recovery rates on each phase, thus causing three-phase voltage unbalance. The results show that combined effects of a small unbalance (5%) in three-phase loads and load composition can be significant. The unbalanced conditions at the interface bus 150 suggests that single-phase representation of transmission system is
not adequate for a system with similar load unbalance and/or load composition unbalance conditions.

Fig. 7.19 Three-phase line-to-ground voltages of bus 158: (a) base case; (b) 5% load unbalance; (c) 5% load unbalance and 5% load composition unbalance
Summary

In this chapter, firstly, a common modeling framework for integrated T&D systems for both power flow and dynamic simulation is proposed, where the transmission system is modeled in three-sequence detail, while distribution systems are represented in three-phase detail. Then an integrated T&D power flow algorithm is solved by iteratively solving a three-sequence power flow for the transmission system and three-phase power flow for the distribution systems. For integrated T&D dynamic simulation, the multi-area Thévenin equivalent approach is employed to solve the integrated T&D networks. The developed power flow and dynamic simulation algorithms have been benchmarked against PSCAD.
The integrated T&D simulation provides the capability to simulate the effects of persistent unbalanced loads and voltages in the distribution systems. This capability has been applied to study FIDVR events under unbalanced fault and unbalanced loads conditions. The results show that combined effects of a small unbalance (5%) in three-phase loads and load composition can cause significant unbalanced conditions in the distribution systems and at the boundary between the transmission and the distribution systems.
CHAPTER 8
ADVANCED EMT-TS HYBRID SIMULATION WITH CAPABILITY OF SWITCHING BACK TO TS SIMULATION

8.1 Background

Compared to TS simulation, EMT simulation is, in general, better suited for modeling and simulating power electronic devices (e.g., HVDC and FACTS) and/or some single-phase devices (e.g., single-phase A/C motors) in detail and capturing their non-linear, fast dynamic responses. Thus, the primary motivation behind switching from TS simulation to EMT-TS hybrid simulation is to take advantage of these capabilities of EMT simulation. Fast dynamics in power system usually settle in a short time-period after the fault is cleared or the disturbance disappears. When the dominant dynamics in the system are in the low frequency range (e.g., below 5 Hz), these components represented in the EMT simulator can be well represented by their corresponding quasi-steady-state (QSS) models [1]. Therefore, it is theoretically feasible to switch from EMT-TS hybrid simulation back to pure TS simulation after the fast dynamics settle down without significantly compromising the simulation accuracy.

Further, in the cases where a relative large-scale (e.g., more than 100 buses) subsystem or a subsystem with several converters is modeled in detail in the EMT simulator, the EMT part of the simulation is usually much slower than the TS part, even when a large-scale subsystem is simulated by TS simulation. Therefore, using the developed EMT-TS hybrid simulation only for a short period after the fault application and removal and switching back to TS simulation for the remainder of the simulation, instead of running EMT-TS
hybrid simulation for the whole simulation period, could significantly reduce the simulation time. Thus, from the simulation efficiency perspective, the option of switching back to TS simulation is attractive.

Switching from pure TS simulation to EMT-TS hybrid simulation provides the “zoom-in” capability to capture the fast dynamic details, while switching from EMT-TS hybrid simulation back to TS simulation allows users to “zoom-out” from the detailed models, as the details have been adequately captured during “zoom-in” period. Such a “zoom-in/zoom-out” capability provides more flexibility to the users in terms of modeling and simulation. The question that remains to be answered is how to realize the proposed switch between the two simulation algorithms automatically during simulation?

Switching from TS to EMT-TS is relatively easy to achieve since it is completed under the pre-fault, normal operating condition. In contrast, switching from EMT-TS simulation to TS simulation is performed when the system is operating under a non-equilibrium condition. A direct approach proposed in [75] is to initialize a phasor modeling representation of the detailed system before switching to the TS simulation. To accomplish such an initialization task, all information to initialize the bus voltages and state variables must be available to the TS simulator and the TS simulator must support initialization under a non-steady-state condition. Thus, this approach is feasible only when both the EMT and the TS simulators are under the users’ control and can be modified to fulfill the initialization process discussed above. Such a strict requirement cannot be satisfied by most of the existing EMT and TS simulators. In fact, in [75], switching from hybrid simulation to pure TS simulation using such an initialization approach is demonstrated using in-house EMT
and TS simulators and the test case is rather simple with only one thyristor controlled series capacitor (TCSC) system modeled in the detailed subsystem.

Another approach of performing the simulation mode switching is proposed in [5], where the main idea is as follows: a phasor model representation of the detailed system is simulated using TS simulation in parallel while EMT-TS hybrid simulation is running. The TS simulation of the detailed system actually serves to replace the aforementioned initialization process. To realize the switching, simulation results of both the phasor representation and the point-on-wave representation of the detailed system are tracked. The switching operation is performed when the simulation results of both representations are within a predefined tolerance and over a set time-period. The detailed and external systems represented using a phasor model are re-connected to form a complete system (same as the original full system) and the remainder of the simulation is conducted using TS simulation with this complete system. Compared to the first approach, this approach requires minor modification to the existing EMT-TS hybrid simulation and the TS simulation algorithms.

However, the second approach also suffers from two significant drawbacks. The first drawback lies in the implicit assumption that simulation results of the two representations of the detailed system will converge at some point after the fast dynamics settle down. However, the convergence is not guaranteed due to the inherent differences between the models used in the EMT and the TS simulations. Secondly, the two subsystems are reconnected to form a full network to continue the TS simulation. This means that both portions of the system must be modeled with the same representation. In other words, this approach
limits the modeling flexibility and is not suitable for integrated transmission and distribution systems. In addition, with the aforementioned approach, the simulation object is in fact changed after switching back to TS simulation. Hence, the TS simulation algorithm has to be augmented to handle the situation of two separate models merged into one, which further complicates the implementation. Besides these two major issues, the details of the implementation are not provided and the choice of the key parameters is not discussed in [5].

8.2 Implementation by Combining Hybrid Simulation and Dynamic Co-simulation

8.2.1 Overview of the Proposed Method

The solution proposed in this research for switching from the EMT-TS hybrid simulation to the TS simulation follows the basic idea of the second approach discussed in the last section. In the proposed approach, the EMT-TS hybrid simulation developed in Chapter 4 and the MATE-based dynamic co-simulation algorithm developed in Chapter 7 are combined. Significant improvements have been made to address the two drawbacks discussed above. The simulation result discrepancy issue between the EMT and TS simulation of the detailed system is addressed from both the modeling and simulation result coordination perspectives:

Firstly, from the modeling perspective, the three-phase phasor modeling is naturally more closely relates to the three-phase point-on-wave models used in the EMT simulation than the three-sequence phasor modeling. The proposed approach supports the three-phase phasor modeling approach developed in Chapter 7. This feature is particularly useful when there are some models (for example, single-phase induction motors), which are better modeled in phase-oriented representation, in the detailed system portion.
Secondly, it is observed from past simulation experiences that major simulation result discrepancies at the post-disturbance stage between the EMT and the TS simulation are usually related to control actions and operation state changes of the critical components modeled in the detailed system. The main reason is that these actions and/or state changes may not be correctly represented by the phasor representation or captured by the TS simulation. Therefore, in the proposed approach, critical discrete event or control signals obtained from EMT simulation results can be fed back to the TS simulation of the detailed system. These signals are used as external control inputs to override the corresponding control or stage change signals in the TS simulation. These important signals can be, for example, a converter blocking signal when an HVDC inverter is undergoing commutation failure or a signal of an A/C motor state change during a FIDVR event.

In addition, re-connecting the two subsystems into a full network becomes unnecessary with the use of the MATE based dynamic simulation. After switching back to the TS simulation mode, the detailed and the external systems are still two individual subsystems under the MATE based simulation framework.

With the proposed simulation algorithm, the full system is split into two parts, i.e., the detailed system and the external system, using the bus splitting method as shown in Fig. 8.1. The detailed system is not only represented in the 3-phase point-on-wave modeling in the chosen EMT simulator, but also modeled in the three-phase phasor representation. The external system is modeled in the three-sequence phasor representation. The whole simulation is divided into three stages, i.e., pre-fault TS simulation stage, EMT-TS hybrid simulation stage, post-disturbance TS simulation stage, as illustrated in Fig. 8.2. The multi-
area dynamic simulation approach is employed at the first and the last simulation stages.

The interactions between the detailed system and the external system for the three stages are shown in Fig. 8.3.

Fig. 8.1 (a) the full network (b) the full network is split into the detailed system and the external system connected by virtual breakers; (c) representations of the detailed system and the external system used in the proposed method
For the second stage, the EMT-TS hybrid simulation algorithm developed in Chapter 4 has been augmented. The hybrid simulation is augmented by running the dynamic
simulation of the detailed system and the switch controller in parallel to the existing hybrid simulation algorithm, as shown in Fig. 8.3. The actual implementation of the augmented algorithm is shown in Fig. 8.4. A three-phase Norton equivalent is used as the external system equivalent in the dynamic simulation (DS) of the detailed system. The three-phase Norton equivalent can be easily obtained for this implementation, as it is a byproduct of the calculation of the three-phase Thévenin equivalent, which is presented in section 3.1 of Chapter 3. The admittance matrix of the three-phase Norton equivalent is added to admittance matrix of the detailed system after switching from the stage 1 to stage 2. The three-phase current source of the Norton equivalent is directly used in the network solution step. When switching from stage 2 to stage 3, the admittance matrix of the detailed system has to be rebuilt to remove the admittance matrix of the three-phase Norton equivalent.

To address the modeling discrepancy and the simulation convergence issue, key discrete event signal(s) obtained from the EMT simulation results can also be used as external control inputs to replace their corresponding control signals in the dynamic simulation of the detailed system, which is also demonstrated in Fig. 8.4. After the effect of the disturbance disappears, boundary conditions obtained from the three-phase dynamic simulation results of the detailed system and the three-sequence TS simulation results of the external system are used as inputs to the simulation switching controller block to identify whether at the next step it is appropriate to switch back to the TS simulation. Details of the simulation switching controller design will be discussed in the next section.
8.2.2 Implementation Details

(1) Network Splitting using the Bus-Splitting Concept

Considering that the EMT-TS hybrid simulation requires common boundary buses shared by the detailed and external systems, bus splitting based network splitting is used for dividing the full system into two parts. For each boundary bus, a dummy bus is created during the network splitting stage. The original boundary bus and the dummy bus are assigned to the detailed system and the external system, respectively, as shown in Fig. 8.1(b). In order to make the splitting scheme compatible with the MATE-based TS co-simulation algorithm, a “virtual breaker” is introduced to link the original boundary bus and the dummy bus.
(2) Simulation switching controller and the switching criteria

After the disturbance or fault is isolated, it generally takes 0.1 - 0.5 s for the system to transit from a fast dynamic state to a slow dynamic state where the system can be adequately represented by phasor models. Thus, a time delay can be used to account for this transition period before switching from EMT simulation to TS simulation. Some a priori knowledge of the simulated system and phenomenon involved can help in choosing an appropriate value for this delay setting. Based on the simulation experiences, the default delay setting is chosen to be 0.2 s.

Once the time delay criterion is met after a fault is cleared, the switching controller begins to compare the boundary conditions obtained from the dynamic simulation of the detailed system and the TS simulation of the external system. Similar to reconnecting a generator to the grid, one primary requirement of reconnecting the detailed and external systems as an integrated system is that boundary conditions of the detailed and external systems should be very close. The key parameters that can represent the boundary bus conditions include the bus voltage (both magnitude and angle), the current through the boundary and the power exchange through the boundary. Given that the Norton equivalent of the external system is used in the dynamic simulation of the detailed system, if the boundary bus voltages obtained by the dynamic simulation of the detailed system and the TS simulation of the external system are the same, the currents and powers through the boundary in both simulations must be the same. Therefore, the voltage is selected as the monitored parameter in this implementation.
The maximum difference of the boundary bus voltages between the detailed system and the external system is used as the indicator for simulation switching. At each step, this indicator is calculated and compared with a preset tolerance (for example 0.005 pu). Furthermore, in order to make sure the boundary conditions of the detailed and external systems truly converge, the maximum voltage difference must be within the preset tolerance for a reasonably long period (for example, several cycles). Once these two criteria are satisfied, the simulation switch controller outputs a signal to indicate that the simulation can be switched to the TS simulation starting from the following time step.

(3) Discrete event signals obtained from the EMT simulation are utilized to enhance the accuracy of the dynamic simulation of the detailed system

One necessary condition for the simulation results obtained from the EMT simulation and the dynamic simulation to converge after the fast transients settle down is that the critical discrete events (such as control actions and operation mode changes), if any, are adequately represented by the dynamic simulation (assuming that these events are accurately captured by the EMT simulation). Based on past experiences, such a condition cannot be satisfied in some cases due to the inherent modeling limitations of the dynamic simulation as well as the modeling differences between the EMT and the dynamic simulations.

The approach employed in the simulation design shown in Fig. 8.2 is straightforward. The critical discrete event signals obtained from the simulation results of the EMT simulation are transferred to the dynamic simulation of the detailed system and used as external control signals either to override the corresponding internal control signals or to
directly control the corresponding devices. In fact, the basic idea behind this approach has been adopted in the combination of TS simulation and long-term dynamic simulation [76]. It should be noted that since only critical discrete event signals, such as A/C motor operation state change and inverter blocking signal due to commutation failure, are considered, the additional communication overhead is negligible. In addition, this function is optional, and it is recommended to be used based on the requirement of the study system.

8.3 Test case

The proposed advanced EMT-TS hybrid simulation with the capability of switching back to TS simulation has been tested with a modified IEEE 9 bus system. Originally, the loads served by bus 5 are represented as an aggregated load and directly connected to the 230 kV bus. In this test case, the aggregated load at bus 5 is replaced by an equivalent subtransmission and distribution system, as shown in Fig. 8.5. Modeling of the subtransmission and distribution system is shown in Fig. 8.6. The loads are connected to an equivalent feeder. As for the load composition, 50% of the total load in terms of active power is represented by single-phase residential A/C motors, while the remainder is modeled as constant impedances in the TS simulation. When the detailed system is simulated by EMT simulation, the POW detailed A/C model is used. On the other hand, when the detailed system is simulated by three-phase dynamic simulation, the A/C performance model developed in section 7.3.3 is used to represent the A/Cs. In the test cases, the TS simulation time step is set at 0.005 s and the EMT simulation time step is chosen to be 20 µs.
8.3.1 Use of Discrete Event Signals to Reconcile the Two Detailed System Simulations

A SLG fault is applied to bus 10 at 0.5 s and cleared after 0.07 s. In order to better study the effects of using discrete event signals from the EMT side to enhance the accuracy of TS simulation, the simulation switching function is disabled. The simulation results without and with sending the A/C motor operation status signals from the EMT side to 3-phase dynamic simulation are shown in Fig. 8.7 and Fig. 8.8, respectively.
In the scenario without sending the A/C motor operation status signals from the EMT side to three-phase dynamic simulation, simulation results of the EMT and the dynamic simulation are significantly different in terms of A/C motor stalling. A/C motors on two phases stalled in the detailed system simulated by the 3-phase dynamic simulation. In contrast, the EMT simulation results show that only the A/C motor on phase \( C \) stalled. This difference results in significant differences between the two simulation results in the three-phase voltages of the boundary bus (bus 5 in this case), as shown in Fig. 8.7. Consequently,
the proposed simulation switching criteria are not satisfied and the simulation keeps running in the hybrid simulation mode till the end of the whole simulation.

In the scenario with sending the A/C motor operation status signals from the EMT side to 3-phase dynamic simulation, the A/C stalling results are coordinated to make sure A/C motors in the dynamic simulation are in the same status as those simulated by the EMT simulation during stage 2. While there are some discrepancies observed in the three-phase boundary bus voltages after the fault is cleared, the discrepancies last only a short time period (approximately 0.15 s) and disappear after the A/C motor on phase C effectively stalls in both the EMT simulation and the three-phase dynamic simulation.
The discrepancies discussed above is related to the A/C motor stalling process, which is simulated in the EMT simulator, but cannot be represented by the performance model of the A/C motor in the dynamic simulation. During the A/C motor stalling process, the reactive power drawn by the A/C motor on phase C increases significantly when the A/C motor speed decreases to lower than 0.5 pu, as shown in Fig. 8.9. The increased reactive power consumption depresses the voltages of both phase A and C of bus 5 after the fault is cleared, as shown in Fig. 8.8(b1)-(b3). On the other hand, before receiving the A/C motor stalling signals from the EMT side, all three A/C motors operate in the running mode in the detailed system simulated by the three-phase dynamic simulation. After the fault is cleared, the bus voltages recover to the levels close to their pre-fault values. These different responses of the A/C motors in the two detailed system simulations contribute to the discrepancies shown in Fig. 8.8(b1)-(b3).

8.3.2 Simulation Switching Criterion

Based on the discussions in Section 8.2.2, the proposed switching criterion is as follows: starting at 0.2 s after the fault is cleared, if the maximum difference of boundary bus voltages (\(max\Delta V\)) obtained by the dynamic simulation of the detailed and the external systems is less than 0.005 pu for more than 2 cycles, simulation will be switched from the EMT-TS hybrid simulation mode to the pure TS simulation mode.

The results in the last section show that the proposed approach can significantly reduce the simulation result discrepancy caused by the modeling difference of some components in the EMT and the TS simulation by coordinating the critical discrete events in the EMT simulation with the TS simulation. With this approach applied to the test case,
Fig. 8.9 EMT simulation results of the A/C motor on phase C
the monitored maximum bus voltage difference during stage 2 is shown in Fig. 8.10. The simulation is switched from the EMT-TS hybrid simulation to the pure TS simulation at 0.805 s, which is 0.235 s after the fault is cleared. It should be noted that the switching is performed under an unbalanced system condition. The simulation results are compared with that simulated by the hybrid simulation approach without switching back to TS simulation, which are shown in Fig. 8.11 and Fig. 8.12. The results of both approaches match closely, demonstrating the effectiveness of the proposed approach.
Fig. 8.10 The maximum difference of boundary buses and the switching signal

Fig. 8.11 Positive sequence voltages of bus 5 and bus 7
8.3.3 Computational Performance

The computational times of a 10 s simulation of the test system with different methods are shown in Table 8.1. Compared to the hybrid simulation without switching back to TS simulation, the proposed approach achieves a 91.86% saving of computational time. In other words, for this specific case, the proposed approach is, on average, twelve times faster than the EMT-TS hybrid simulation without the capability of switching back to TS simulation.
Table 8.1 The computational times of different methods

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>Computational time /s</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMT-TS hybrid simulation without switching back to TS simulation</td>
<td>189.2</td>
</tr>
<tr>
<td>EMT-TS hybrid simulation with switching back to TS simulation</td>
<td>15.4</td>
</tr>
<tr>
<td>Three-phase TS simulation</td>
<td>1.2</td>
</tr>
</tbody>
</table>

8.4 Summary

In this chapter, an advanced EMT-TS hybrid simulation algorithm with the capability of switching back to the TS simulation is developed by combining the EMT-TS hybrid simulation algorithm and the MATE-based dynamic simulation algorithm developed in the last chapter. With this new algorithm, a dynamic simulation is divided into three stages, i.e., pre-fault TS simulation stage, EMT-TS hybrid simulation stage and post-disturbance TS simulation stage. The MATE based dynamic simulation approach is employed for the first and the last simulation stages. In order to address the initialization issue of switching from EMT simulation to TS simulation, a three-phase phasor representation of the detailed system is simulated in parallel of the EMT-TS hybrid simulation. A three-phase Norton equivalent of the external system is used to represent the external system. Further, it is proposed to coordinate the critical discrete events between the EMT and dynamic simulation of the detailed system, to address the simulation result discrepancy issue caused by the modeling differences in the EMT and the TS simulation. Lastly, the test results show that, with the developed simulation switch feature, the total computational time is significantly reduced compared to running the hybrid simulation for the whole simulation period, while a good accuracy is maintained.
CHAPTER 9
CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

Electromagnetic transient and electro-mechanical transient stability hybrid simulation has been investigated in this research. With the hybrid simulation approach, both the fast transients and slow dynamics can be adequately captured by the EMT and TS simulator, respectively, while simultaneously addressing the dilemma of handling both the detailed modeling and the large scale of the system being examined. The proposed approach and the developed simulation tool together provide necessary simulation capabilities to adequately investigate the interactions between the transmission and distribution systems, such as the FIDVR problem, as well as the dynamic performance of power systems interfaced with power electronic devices, such as HVDC systems.

The main contributions of this research are summarized as follows:

1. In Chapter 3, a three-phase Thévenin equivalent and a three-sequence current source equivalent for representing the external system and the detailed system, respectively, are proposed for hybrid simulation. Correspondingly, a three-sequence TS simulation algorithm is developed. These analytical developments facilitate the simulation of unsymmetrical faults inside the detailed system without extensively extending the boundary and the extent of the detailed system.

2. A new interaction protocol design combining both the serial and parallel interaction protocols in a flexible manner is developed to achieve good simulation performance without comprising the accuracy.
3. An open source tool for hybrid simulation has been developed in Chapter 4. A generic interface is designed for integrating with different EMT simulators.

4. The proposed hybrid simulation approach has been applied to a detailed FIDVR study on the WECC system in Chapter 5. Some significant insights on the evolution of a FIDVR event triggered by a normally cleared SLG fault are uncovered. With a typical delta-wye grounded connection for step down transformers, the event begins with A/Cs stalling on two directly impacted phases, followed by A/C stalling propagating to the unfaulted phase. Further, the effects of the load composition and the point-on-wave of fault inception are also investigated.

5. A common modeling framework for integrated T&D system power flow and dynamic simulation is proposed. Then an integrated T&D power flow algorithm is solved by iteratively solving a three-sequence power flow for the transmission system and a three-phase power flow for each distribution system. For integrated T&D dynamic simulation, the multi-area Thévenin equivalent approach is employed to solve the integrated T&D networks. The integrated T&D simulation provides the capability to simulate the effects of persistent unbalanced loads and voltages in the distribution systems. This capability has been applied to study FIDVR events under unbalanced fault and unbalanced loads conditions.

6. An advanced EMT-TS hybrid simulation with the capability to switch back to the TS simulation has been developed in Chapter 8. The new simulation algorithm is developed by combining the EMT-TS hybrid simulation algorithm and
the MATE-based dynamic simulation algorithm. The proposed algorithm effectively addresses the simulation efficiency issue of the original EMT-TS simulation for a long dynamic simulation.

9.2 Future Work

To further enhance the functions and performance of the proposed hybrid simulation and integrated T&D simulation approaches and to expand their applications to other promising application areas, the following subjects can be considered:

(1) *Distributed hybrid simulation*

In a large-scale power system like WECC, PV and wind plants as well as other power electronic devices are usually interfaced with the system at different locations. Presently, when multiple PV or wind plants at different locations are simulated using the hybrid simulation approach, they have to represented in one EMT simulator. This increases the computational burden of the EMT simulation and thus affects the overall simulation efficiency. An alternative to address this issue is to enhance the EMT simulation part by using a distributed computing approach.

As the socket communication by nature supports connecting multiple clients to one server, the developed hybrid simulation can therefore be flexibly extended to a distributed version as illustrated in Fig. 9.1. With this distributed hybrid simulation, detailed subsystems at different locations of the system can be simulated by different EMT simulators independently. Consequently, the simulation burden in one EMT simulator can be significantly reduced compared to the present standalone hybrid simulation.
Fig. 9.1 A schematic showing a distributed hybrid simulation platform

(2) Exploiting multi-core parallel computing to accelerate MATE-based dynamic simulation

There is inherent parallelism in the MATE-based dynamic simulation at the subsystem level. Such parallelism can and should be utilized to accelerate dynamic simulation efficiency, especially considering the even larger scale of integrated transmission and distribution systems. Presently, computers and laptops are generally equipped with a multi-core CPU. The multi-core parallel computing capability can be exploited to accelerate MATE-based dynamic simulation.

(3) Application of the integrated transmission and distribution system simulation capability to comprehensively study the impact of distributed generation resources

To further facilitate integration of distributed generation resources in the distribution systems and to better understand their impacts on the bulk power systems, there are some critical questions remain to be answered. First, under what conditions does the aggregated composite load model becomes inappropriate and when should the distribution systems, at least those in the vicinity of the fault, be modeled in detail? Second, what is the cost to benefit of integrated transmission and distribution system dynamic simulation?
Third, how can the industry smoothly transit from the existing transmission and distribution independent modeling and simulation practice to the new paradigm of integrated modeling and simulation? The modeling and simulation capability developed in Chapter 7 can provide more insights to the three questions above.
REFERENCES


[34] Alternative Transients Program (ATP), Available from: http://www.emtp.org/


[80] WECC Load Modeling task Force. AC Unit Model specifications, April 2008

APPENDIX A

IEEE 9 BUS SYSTEM DATA
### Table A1 Bus data summary

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Nominal kV</th>
<th>Load MW</th>
<th>Load MVar</th>
<th>Gen MW</th>
<th>Gen MVar</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>BUS-1</td>
<td>16.5</td>
<td>0</td>
<td>0</td>
<td>71.64</td>
<td>27.1</td>
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<tr>
<td>2</td>
<td>BUS-2</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>163</td>
<td>6.59</td>
</tr>
<tr>
<td>3</td>
<td>BUS-3</td>
<td>13.8</td>
<td>0</td>
<td>0</td>
<td>85</td>
<td>-10.92</td>
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<td>4</td>
<td>BUS-4</td>
<td>230</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>5</td>
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<td>230</td>
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<td>50</td>
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<td>0</td>
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<tr>
<td>6</td>
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<td>230</td>
<td>90</td>
<td>30</td>
<td>0</td>
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<td>7</td>
<td>BUS-7</td>
<td>230</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>BUS-8</td>
<td>230</td>
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<td>35</td>
<td>0</td>
<td>0</td>
</tr>
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<td>9</td>
<td>BUS-9</td>
<td>230</td>
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<td>0</td>
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<td>0</td>
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</tbody>
</table>

### Table A2 Branch three sequence data summary

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<thead>
<tr>
<th>From Name</th>
<th>To Name</th>
<th>Positive and negative sequence data</th>
<th>Zero sequence data</th>
<th>Tap</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>R/pu</td>
<td>X/pu</td>
<td>B/pu</td>
</tr>
<tr>
<td>BUS-1</td>
<td>BUS-4</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>BUS-2</td>
<td>BUS-7</td>
<td>0</td>
<td>0.0625</td>
<td>0</td>
</tr>
<tr>
<td>BUS-3</td>
<td>BUS-9</td>
<td>0</td>
<td>0.0586</td>
<td>0</td>
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<tr>
<td>BUS-4</td>
<td>BUS-5</td>
<td>0.01</td>
<td>0.085</td>
<td>0.176</td>
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<td>BUS-4</td>
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<td>0.092</td>
<td>0.158</td>
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<td>BUS-7</td>
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<td>0.161</td>
<td>0.306</td>
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<tr>
<td>BUS-6</td>
<td>BUS-9</td>
<td>0.039</td>
<td>0.17</td>
<td>0.358</td>
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<tr>
<td>BUS-7</td>
<td>BUS-8</td>
<td>0.0085</td>
<td>0.072</td>
<td>0.149</td>
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<td>BUS-8</td>
<td>BUS-9</td>
<td>0.0119</td>
<td>0.1008</td>
<td>0.209</td>
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### Table A4 Generator dynamic data

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<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Bus</td>
<td>BUS-1</td>
<td>BUS-2</td>
<td>BUS-3</td>
</tr>
<tr>
<td>Nominal kV</td>
<td>16.5</td>
<td>18</td>
<td>13.8</td>
</tr>
<tr>
<td>PU Volt</td>
<td>1.04</td>
<td>1.025</td>
<td>1.025</td>
</tr>
<tr>
<td>MVA Base</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>H</td>
<td>23.64</td>
<td>6.4</td>
<td>3.01</td>
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<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ra</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Xd</td>
<td>0.146</td>
<td>0.8958</td>
<td>1.313</td>
</tr>
<tr>
<td>Xq</td>
<td>0.0969</td>
<td>0.8645</td>
<td>1.258</td>
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<td>Xdp</td>
<td>0.0608</td>
<td>0.1189</td>
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<td>Xqp</td>
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<td>0.1969</td>
<td>0.25</td>
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<td>Xdp0</td>
<td>0.05</td>
<td>0.089</td>
<td>0.107</td>
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<tr>
<td>XI</td>
<td>0.0336</td>
<td>0.0521</td>
<td>0.0742</td>
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<tr>
<td>Tdop</td>
<td>8.96</td>
<td>6</td>
<td>5.89</td>
</tr>
<tr>
<td>Tqop</td>
<td>--</td>
<td>0.54</td>
<td>0.6</td>
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<tr>
<td>Tdopp</td>
<td>0.04</td>
<td>0.033</td>
<td>0.033</td>
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<tr>
<td>Tqopp</td>
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<td>0.078</td>
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### Table A5 Generator sequence impedance data

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<th>Number of Bus</th>
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<th>Positive Sequence</th>
<th>Negative Sequence</th>
<th>Zero Sequence</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td>r</td>
<td>x</td>
<td>r</td>
</tr>
<tr>
<td>1</td>
<td>BUS-1</td>
<td>0</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>BUS-2</td>
<td>0</td>
<td>0.09</td>
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</tr>
<tr>
<td>3</td>
<td>BUS-3</td>
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<td>0.11</td>
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</table>

### Table A6 Load sequence admittance data

<table>
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<th>Number of Bus</th>
<th>Name of Bus</th>
<th>Positive Sequence</th>
<th>Negative Sequence</th>
<th>Zero Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g</td>
<td>b</td>
<td>g</td>
</tr>
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<td>5</td>
<td>BUS-5</td>
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<td>1.261</td>
</tr>
<tr>
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<td>BUS-6</td>
<td>0.877</td>
<td>-0.292</td>
<td>0.877</td>
</tr>
<tr>
<td>8</td>
<td>BUS-8</td>
<td>0.969</td>
<td>-0.339</td>
<td>0.969</td>
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</tbody>
</table>
Fig. A1. The control block diagram of the IEEE 1968 type 1 exciter

<table>
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<tr>
<th>Bus Name</th>
<th>TR</th>
<th>KA</th>
<th>TA</th>
<th>VRMAX</th>
<th>VRMIN</th>
<th>KE</th>
<th>TE</th>
<th>KF</th>
<th>TF</th>
<th>E1</th>
<th>SE(E1)</th>
<th>E2</th>
<th>SE(E2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS-1</td>
<td>0.06</td>
<td>20</td>
<td>0.2</td>
<td>5</td>
<td>-4</td>
<td>1</td>
<td>0.314</td>
<td>0.063</td>
<td>0.35</td>
<td>3</td>
<td>0.104</td>
<td>4</td>
<td>0.293</td>
</tr>
<tr>
<td>BUS-2</td>
<td>0.06</td>
<td>20</td>
<td>0.2</td>
<td>5</td>
<td>-4</td>
<td>1</td>
<td>0.314</td>
<td>0.063</td>
<td>0.35</td>
<td>3</td>
<td>0.104</td>
<td>4</td>
<td>0.293</td>
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<td>5</td>
<td>-4</td>
<td>1</td>
<td>0.314</td>
<td>0.063</td>
<td>0.35</td>
<td>3</td>
<td>0.104</td>
<td>4</td>
<td>0.293</td>
</tr>
</tbody>
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APPENDIX B

COMPOSITE LOAD MODEL DATA
Table A8: The dynamic data of three-phase induction motor B and C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Stator resistance/pu</td>
<td>0.015</td>
</tr>
<tr>
<td>Stator leakage reactance/pu</td>
<td>0.091</td>
</tr>
<tr>
<td>Mutual reactance/pu</td>
<td>6.319</td>
</tr>
<tr>
<td>Rotor mutual reactance/pu</td>
<td>0.1418</td>
</tr>
<tr>
<td>Second cage unsaturated reactance/pu</td>
<td>0.0539</td>
</tr>
<tr>
<td>First cage resistance/pu</td>
<td>0.0507</td>
</tr>
<tr>
<td>Second cage resistance/pu</td>
<td>0.0095</td>
</tr>
<tr>
<td>Damping/pu</td>
<td>0.0062</td>
</tr>
<tr>
<td>Polar moment of inertia (J = 2 H)/s</td>
<td>0.9902</td>
</tr>
</tbody>
</table>

Table A9: The dynamic data of three-phase induction motor D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance/pu</td>
<td>0.066</td>
</tr>
<tr>
<td>Stator leakage reactance/pu</td>
<td>0.046</td>
</tr>
<tr>
<td>Mutual reactance/pu</td>
<td>3.86</td>
</tr>
<tr>
<td>Rotor mutual reactance/pu</td>
<td>0.122</td>
</tr>
<tr>
<td>Second cage unsaturated reactance/pu</td>
<td>0.105</td>
</tr>
<tr>
<td>First cage resistance/pu</td>
<td>0.029</td>
</tr>
<tr>
<td>Second cage resistance/pu</td>
<td>0.018</td>
</tr>
<tr>
<td>Damping/pu</td>
<td>0.008</td>
</tr>
<tr>
<td>Polar moment of inertia (J = 2 H)/s</td>
<td>0.2</td>
</tr>
</tbody>
</table>

1 The three phase motors in the composite load model are represented by the built-in squirrel case induction motor of PSCAD. The dynamic model data of the motor B and C is based on the provided typical data of 4.16 kV, 4-Pole, 1000 HP Machine.

2 It is based on the typical data of 4.16 kV, 4-Pole, 500 HP Machine in PSCAD, except the polar moment of inertia changed to 0.2 s.
APPENDIX C

DYNAMIC MODELS OF SINGLE-PHASE AIR CONDITIONER MOTOR
Table A10 The parameters of the point-on-wave detailed A/C model

<table>
<thead>
<tr>
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<tr>
<td>Base voltage</td>
<td>230 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Main to auxiliary winding turns</td>
<td>1.22</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>0.07 m</td>
</tr>
<tr>
<td>Rotor shaft length</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Stator winding resistance</td>
<td>0.3 ohm</td>
</tr>
<tr>
<td>Rotor winding static resistance</td>
<td>0.3 ohm</td>
</tr>
<tr>
<td>Rotor cage resistance coefficient A</td>
<td>2.5</td>
</tr>
<tr>
<td>Rotor cage resistance coefficient B</td>
<td>1.5</td>
</tr>
<tr>
<td>Magnetizing reactance</td>
<td>30 ohm</td>
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<tr>
<td>Stator leakage reactance</td>
<td>0.5 ohm</td>
</tr>
<tr>
<td>Rotor leakage reactance</td>
<td>0.5 ohm</td>
</tr>
<tr>
<td>Saturation at rated flux</td>
<td>0.03</td>
</tr>
<tr>
<td>Saturation at 1.2 rated flux</td>
<td>0.1</td>
</tr>
<tr>
<td>Speed dependent load</td>
<td>4 N*m</td>
</tr>
<tr>
<td>Angle dependent load</td>
<td>12 N*m</td>
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</table>
Table A11 The parameters of the single-phase A/C performance model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Voltage filter time constant, sec.</td>
<td>Tv</td>
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</tr>
<tr>
<td>Frequency filter time constant, sec.</td>
<td>Tf</td>
<td>0.05</td>
</tr>
<tr>
<td>Compressor power factor</td>
<td>CompPF</td>
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</tr>
<tr>
<td>Compressor stall voltage</td>
<td>Vstall</td>
<td>0.65</td>
</tr>
<tr>
<td>Compressor stall resistance, p.u.</td>
<td>Rstall</td>
<td>0.124</td>
</tr>
<tr>
<td>Compressor stall reactance, p.u.</td>
<td>Xstall</td>
<td>0.114</td>
</tr>
<tr>
<td>Compressor stall time delay, sec.</td>
<td>Tstall</td>
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</tr>
<tr>
<td>Vstall adjustment proportional to loading factor</td>
<td>LFadj</td>
<td>0.3</td>
</tr>
<tr>
<td>Real power coefficient for running state 1, p.u. P/p.u.V</td>
<td>Kp1</td>
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</tr>
<tr>
<td>Real power exponent for running state 1</td>
<td>Np1</td>
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</tr>
<tr>
<td>Reactive power coefficient for running state 1, p.u. Q/p.u.V</td>
<td>Kq1</td>
<td>6</td>
</tr>
<tr>
<td>Reactive power exponent for running state 1</td>
<td>Nq1</td>
<td>2</td>
</tr>
<tr>
<td>Real power coefficient for running state 2, p.u. P/p.u.V</td>
<td>Kp2</td>
<td>12</td>
</tr>
<tr>
<td>Real power exponent for running state 2</td>
<td>Np2</td>
<td>3.2</td>
</tr>
<tr>
<td>Reactive power coefficient for running state 2, p.u. Q/p.u.V</td>
<td>Kq2</td>
<td>11</td>
</tr>
<tr>
<td>Reactive power exponent for running state 2</td>
<td>Nq2</td>
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<tr>
<td>Compressor motor “breakdown” voltage, p.u.</td>
<td>Vbrk</td>
<td>0.86</td>
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<tr>
<td>Fraction of motors that are capable of restarting</td>
<td>Frst</td>
<td>0</td>
</tr>
<tr>
<td>Voltage at which motors can restart, p.u.</td>
<td>Vrst</td>
<td>0.9</td>
</tr>
<tr>
<td>Time delay before motors can restart, sec.</td>
<td>Trst</td>
<td>0.4</td>
</tr>
<tr>
<td>Real power frequency sensitivity, p.u. P/p.u.f</td>
<td>CmpKpf</td>
<td>1</td>
</tr>
<tr>
<td>Reactive power frequency sensitivity, p.u. Q/p.u.f</td>
<td>CmpKqf</td>
<td>-3.3</td>
</tr>
<tr>
<td>Voltage 1 at which contactors open, p.u.</td>
<td>Vc1off</td>
<td>0.45</td>
</tr>
<tr>
<td>Voltage 2 at which contactors open, p.u.</td>
<td>Vc2off</td>
<td>0.35</td>
</tr>
<tr>
<td>Voltage 1 at which contactors close, p.u.</td>
<td>Vc1on</td>
<td>0.5</td>
</tr>
<tr>
<td>Voltage 2 at which contactors close, p.u.</td>
<td>Vc2on</td>
<td>0.4</td>
</tr>
<tr>
<td>Compressor motor heating time constant, sec.</td>
<td>Tth</td>
<td>10</td>
</tr>
<tr>
<td>Temperature at which comp. motors begin tripping</td>
<td>Th1t</td>
<td>1.3</td>
</tr>
<tr>
<td>Temperature at which all motors are tripped, p.u. of rated</td>
<td>Th2t</td>
<td>4.3</td>
</tr>
<tr>
<td>Fraction of compressor motors with under-voltage relays</td>
<td>fuvr</td>
<td>0</td>
</tr>
</tbody>
</table>
APPENDIX D

MULTI-AREA THÉVENIN EQUIVALENT
The multi-area Thévenin equivalent (MATE) concept is developed based on the diakoptics concept and the formulation of modified nodal analysis (MNA)[70]. MATE re-formulates and extends the diakoptics approach to make it easier to understand and program into an algorithm.

MATE is mainly used to meet two objectives: one is to subdivide the original system into subsystems, which are connected via the link branches; the other is to help reconcile the individual solutions of subsystems into a full-system simultaneous solution at the network solution stage. The formulation of the MATE based algorithm can be found in [68]. A system consisting of three areas shown in Fig. D1 is used to illustrate main idea and key steps of the MATE formulation. The system can be mathematically represented by the modified nodal equations given in (D.1)

\[
\begin{bmatrix}
Y_1 & 0 & 0 & A_1 \\
0 & Y_2 & 0 & A_2 \\
0 & 0 & Y_3 & A_3 \\
A_1^T & A_2^T & A_3^T & Z_{Link}^0
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
-I_{Link}
\end{bmatrix} =
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
0
\end{bmatrix}
\]

where \(Y_k\) is the admittance matrix of subsystem \(k, k \in S_{sub}\) and \(S_{sub} = \{1, 2, 3\}\); \(V_k\) is the bus voltage vector of subsystem \(k\); \(I_k\) is the bus current injection vector of subsystem.
$k; I_{Link}$ is the vector of current flow through the link branches; the impedances of the link branches forms a diagonal matrix $Z_{Link}^0; A_k$ is the incidence matrix which relates the buses of subsystem $k$ to the link branches. The last row represents the link subsystem.

After Gaussian elimination is applied to the last row corresponding to the link subsystem, a new set of equations given in (D.2) is obtained.

$$
\begin{bmatrix}
  Y_1 & 0 & 0 & A_1 \\
  0 & Y_2 & 0 & A_2 \\
  0 & 0 & Y_3 & A_3 \\
  0 & 0 & 0 & Z_{Link}
\end{bmatrix}
\begin{bmatrix}
  V_1 \\
  V_2 \\
  V_3 \\
  -I_{Link}
\end{bmatrix}
= 
\begin{bmatrix}
  I_1 \\
  I_2 \\
  I_3 \\
  V_{Link}
\end{bmatrix}
$$

where $Z_{Link}$ and $V_{Link}$ are defined below, with

$$Z_{th,k} = A_k^T(Y_k)^{-1}A_k$$  \hspace{1cm} (D.3)

$$Z_{Link} = Z_{Link}^0 + \sum_{k \in S_{sub}} Z_{th,k}$$  \hspace{1cm} (D.4)

$$V_{th,k} = A_k^T(Y_k)^{-1}I_k$$  \hspace{1cm} (D.5)

$$V_{Link} = \sum_{k \in S_{sub}} V_{th,k}$$  \hspace{1cm} (D.6)

In the equations above, $Z_{th,k}$ and $V_{th,k}$ represent the Thévenin equivalent of the subsystem $k$ viewed by the link subsystem. $Z_{Link}$ and $V_{Link}$ can be regarded as the reduced system of the original system with only the link branches and the boundary buses preserved.

After all subsystems are solved with the link branches assumed to be open, $Z_{th,k}$ and $V_{th,k}$ of the subsystems can be obtained. Subsequently, the currents of the link branches can be calculated by solving (D.7)

$$-Z_{Link}I_{Link} = V_{Link}$$  \hspace{1cm} (D.7)
The last step is to inject the currents of link branches into the subsystems accordingly and update the network solution results of the subsystems based on the superposition theorem.

The following are some clarifications on the concept of MATE:

(1) Although all the subsystems are assumed to be modeled in the same representation in the derivation above, modeling the subsystems in the same manner is neither a pre-assumption nor a requirement of this approach. Subsystems modeled in mixed detail can co-exist, and the formulation and processing procedures need to be changed accordingly.

(2) Calculation of the Thévenin equivalents of the subsystems is not necessarily the same as shown in (D.4) and (D.6). In fact, the Thévenin equivalent seen from the boundary buses of a subsystem can be calculated first, and then transformed to a form as viewed from the link subsystem perspective. Correspondingly, (D.4) and (D.6) can be reformulated to become (D.8) and (D.9), respectively.

\[
Z_{th,k} = \tilde{A}_k^T Z_{thB,k} \tilde{A}_k \\
V_{th} = \tilde{A}_k^T V_{thB,k}
\]

where \(Z_{thB,k}\) and \(V_{thB,k}\) are the Thévenin equivalent impedance matrix and voltage source vector viewed from the boundary bus(es) of subsystem \(k\), respectively; \(\tilde{A}_k\) is the incidence matrix relating the the boundary bus(es) of subsystem \(k\) to the link branches. This approach is used in the following development.

(3) Based on the physical definition, the voltage sources \(V_{thB,k}\) are the same as the boundary bus voltages obtained from the subsystem network solution with the link
branches assumed to be open. Thus, the voltage sources of the Thévenin equivalent can be obtained as a byproduct of the subsystem network solution.

(4) If there are more than one representation coordinates utilized in the subsystems (e.g., three-phase and three-sequence), a common representation coordinate should be predefined for the coordination purpose. Thévenin equivalents of the subsystems must be transformed to the target coordinate representation, if their original representation coordinate is different from the target one.

(5) Compared to single-network solution, the MATE based solution mainly changes the procedure of solving the network equations. The integration step and the overall solution procedure are not changed. Thus, the convergence characteristic of the MATE approach based network solution is the same as simulating the system as a single network.