A General Initialization Scheme for Electromagnetic Transient Simulation: Towards Large-Scale Hybrid AC-DC Grids

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Abstract—With the advent of large-scale hybrid AC-DC grids, electromagnetic transient (EMT) simulation is required to accurately describe the dynamics of systems. However, EMT steady-state initialization for hybrid AC-DC systems is difficult and time consuming when the system scale is very large. To provide a stable snapshot for EMT simulation with nonlinear components and black-box components, this paper proposes a general initialization scheme for EMT simulation (EMT-GIS) that can be implemented in electromagnetic transient program (EMTP)-type simulators. First, an integrated power flow (IPF) algorithm is introduced to provide steady-state results. Then, an initialized snapshot calculation-and-splicing mechanism is designed for EMT-GIS. The proposed EMT-GIS is tested using a hybrid AC-DC system in China on the CloudPSS simulation platform. Test results verify the effectiveness of the proposed EMT-GIS.

Index Terms—Electromagnetic transient simulation, hybrid AC-DC grid, integrated power flow, steady-state initialization.

I. INTRODUCTION

With the continuous development of power electronics technologies, conventional AC grids are gradually being transformed into large-scale hybrid AC-DC grids [1], [2]. Due to the interactive coupling between AC and DC subsystems, as well as the complicated dynamics of power electronics and possible cascading failures, conventional electromechanical transient simulation or electromechanical-electromagnetic hybrid simulation cannot satisfy the accurate transient analyses for hybrid AC-DC grids. Therefore, fully electromagnetic transient (EMT) simulations are urgently required [3], [4].

The initialization process, as a prerequisite for further dynamic analyses, is one of the most important and challenging aspects of EMT simulation for large-scale hybrid AC-DC systems [5]. Existing commercial EMT simulation platforms usually provide the default zero-state ramping scheme for EMT initialization [6]. As a simple but effective approach, the ramping scheme can rapidly initialize the small-scale EMT model. However, the initialization efficiency of the ramping scheme is low when the system scale is very large, and the complex dynamics and control logic in hybrid AC-DC systems may lead to ramping initialization failures.

Another popular initialization scheme for EMT simulation is the steady-state initialization scheme, which initializes the EMT model directly from the steady state with a given snapshot. In [7], a steady-state initialization method considering the harmonic power flow is proposed. In [8], a transition-state-calculation-based initialization approach is proposed. However, the above two methods cannot be applied to the hybrid AC-DC system because the state variables of the DC control system cannot be completely derived from the power flow results. Towards HVDC systems, an automatic EMT initialization method for LCC-HVDC is introduced in [9], and an EMT initialization scheme for MMC-HVDC is proposed in [10]. Nevertheless, the EMT steady-state initialization for the hybrid AC-DC system is not considered in either [9] or [10].

In addition, when performing bulk-grid-level simulation, there exist various black-box components (e.g., factory private models and hardware-in-the-loop devices) [11] whose detailed models are unavailable because of privacy protection. Obviously, the black-box components also present difficulties to the EMT initialization and simulation of hybrid AC-DC systems, and there is no relevant research thus far.

Therefore, one critical issue is how to effectively initialize the EMT model of a large-scale hybrid AC-DC system with nonlinear components and black-box components. To address this issue, a general initialization scheme for EMT simulation (EMT-GIS) is proposed in this paper, and an integrated power flow (IPF) algorithm is proposed to provide the power flow results of the entire grid. Then, an initialized snapshot calculation-and-splicing mechanism is introduced to rapidly force the entire system into the steady state.

The contributions of this paper are as follows.

- A general scheme for EMT initialization (EMT-GIS) is proposed, which is effective for large-scale hybrid AC-DC system cases.
- An IPF algorithm with the Jacobian-Free Newton-GMRES(m) (JFNG(m)) method is proposed, which provides the whole-system power flow results without knowledge of modeling details of the black-box components.
• An initialized snapshot calculation-and-splicing mechanism is introduced, which improves the initialization efficiency of EMT-GIS.

The rest of this paper is organized as follows. Section II introduces the overall framework of EMT-GIS. Section III proposes the IPF algorithm with a JFNG(m)-based approach. Section IV proposes the initialized snapshot calculation-and-splicing mechanism. In Section V, a hybrid AC-DC system in China is tested and the effectiveness of the proposed EMT-GIS is verified. Section VI provides the conclusion.

II. OVERALL FRAMEWORK OF EMT-GIS

The EMT-GIS is designed to initialize the EMT model of large-scale hybrid AC-DC systems. In a hybrid AC-DC system, subsystems with numerous power electronics (e.g., HVDC systems and renewable energy systems) are embedded in a conventional three-phase AC system (i.e. the main system).

Considering the model availability of the components, we define two kinds of components: the black-box components, whose detailed models are hidden or private, and the white-box components, whose detailed models are available. Then, we can define the regions composed of black-box components (RBCs) and those composed of white-box components (RWCs). The RBCs and subsystems with complex dynamics (e.g., the control dynamics of HVDC) compose the generalized regions of black-box components (GRBCs). The proposed EMT-GIS deals with the main system and GRBCs by different approaches.

The framework of EMT-GIS is shown in Fig. 1. First, the proposed IPF algorithm, which considers the GRBC subsystems, provides the whole-system power flow results for EMT-GIS. Then, in the simulation process, the AC main system is initialized from the steady-state snapshot that is calculated from the IPF results, while the GRBC subsystems are initialized from the zero state by a ramping approach. After all subsystems reach their initialized snapshots, a snapshot-splicing mechanism is introduced to splice the snapshots of each subsystem and complete the EMT initialization. Benefiting from the IPF algorithm and snapshot-calculation-and-splicing mechanism, EMT-GIS exhibits the following characteristics:

- **Model-free characteristic:** EMT-GIS is applicable to large-scale hybrid AC-DC systems containing subsystems with complex dynamics, black-box components or even practical physical models.
- **Platform-free characteristic:** EMT-GIS can be implemented in any EMT simulation platform, and in this paper, we utilize the cloud-computing-based EMT simulation platform (CloudPSS) [12] as a testbed.

III. DECOMPOSITION-AND-COORDINATION-BASED INTEGRATED POWER FLOW ALGORITHM FOR EMT-GIS

In this section, we first introduce the details of decomposition and coordination in the hybrid AC-DC system with black-box components. Then, a JFNG(m)-based IPF algorithm is proposed to obtain the power flow results of the whole system.

A. Decomposition and Coordination

When decomposing the whole hybrid AC-DC system, an RWC system can be considered as the main system with an effective power flow solver (e.g., AC-DC power flow solver for HVDC systems) or as the GRBC system if the detailed model is too complex to solve. Thus, in this section, we consider the decomposition and coordination among the main system and GRBC systems.

Generally, a system decomposition is shown in Fig. 2, where the main system is connected to GRBC systems through boundary buses. The set of GRBCs is denoted by $N_B = \{1, 2, \ldots, n\}$, which can also represent the boundary buses.

The decomposition is achieved by boundary bus tearing. For $i \in N_B$, the boundary bus $B_i$ is torn into $B_{io}$ for GRBCi and $B_i$ for the main system, and the corresponding injected power and voltage of each system can be represented as $(\bar{P}_i + j\bar{Q}_i, \bar{V}_i, \angle \bar{\theta}_i)$ and $(P_i + jQ_i, V_i, \angle \theta_i)$, as shown in Fig. 2. Supposing that the boundary voltages $V_i, \angle \theta_i$ and $V_i, \angle \theta_i$ are provided, the power flow of the main system can be solved by setting the boundary buses as slack buses, and the injected power $\bar{P}_i + j\bar{Q}_i$ of the GRBCi system can be obtained by digital simulation tools or practical physical simulation.

Obviously, to derive the power flow results of the whole system, it is necessary for the systems’ variables to satisfy the boundary convergence condition, which is written in vector form as follows:

$$V = \bar{V}, \theta = \bar{\theta}$$

$$P + \bar{P} = 0, Q + \bar{Q} = 0$$

where $V = \text{col}(V_i), \bar{V} = \text{col}(\bar{V}_i), \theta = \text{col}(\theta_i), \bar{\theta} = \text{col}(\bar{\theta}_i), P = \text{col}(P_i), \bar{P} = \text{col}(\bar{P}_i), Q = \text{col}(Q_i)$ and $\bar{Q} = \text{col}(\bar{Q}_i) \in \mathbb{R}^n$ for $i \in N_B$.

If convergence condition (1) is not completely satisfied, with the given equal boundary voltages that satisfy (1a), the boundary power deviation vectors are $\Delta P = P + \bar{P}$ and $\Delta Q = Q + \bar{Q}$. Then, the boundary coordination equations (BCEs) can be expressed as (2).

$$\Phi(V^T, \theta^T) = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} P + \bar{P} \\ Q + \bar{Q} \end{bmatrix} = 0$$

where $\Phi(V^T, \theta^T) \in \mathbb{R}^{2n}$. Thus, the solution of the entire system’s power flow is equivalent to the solution of BCEs (2), and the procedures of integrated power flow (IPF) are as shown in Fig. 3.
Remark 1. The power flow results from IPF benefit EMT-GIS. The BCES are implicit functions of \( V \) and \( \theta \). However, the coordinator for obtaining the corrections in Fig. 3 is difficult to design because of the unavailability of detailed internal models of the GRBC systems; thus, the Jacobian matrix of the whole system cannot be derived during the Newton-Raphson solving process. To solve the aforementioned problem, the Jacobian-Free Newton-GMRES(m) (JFNG(m)) algorithm is utilized to solve the BCES in the following subsection.

B. JFNG(m) Method for Boundary Coordination

JFNG(m) is a nonlinear equations solver that does not explicitly form the Jacobian matrix. An adaptive preconditioner is constructed in [13] for the JFNG(m) method to enhance the convergence. In this subsection, the JFNG(m) method with the adaptive preconditioner is utilized to solve the BCES in the IPF process. The details of the IPF-JFNG(m) algorithm are shown in Algorithm 1.

Remark 2. The power flow results of the IPF-JFNG(m) algorithm enable the EMT initialization of the large-scale hybrid AC-DC system containing black-box components. The convergence of the IPF-JFNG(m) algorithm is equivalently discussed in [13] and [14].

IV. INITIALIZED SNAPSHOT CALCULATION-AND-SPLICING MECHANISM

In this section, an initialized snapshot calculation-and-splincing mechanism is developed, which is also a significant part of EMT-GIS. First, each respective subsystem calculates its initialized snapshot according to the IPF results. Then, a snapshot-splincing approach is introduced.

A. Initialized Snapshot Calculation

We introduce the initialized snapshot calculation in the following two parts.

1) Three-Phase AC Main System. The main system consists of three-phase AC components (e.g. synchronous generators and three-phase transformers). Considering the scenarios with three-phase symmetrical operation, the electrical variables can be expressed in the phasor form. Thus, given the steady-state power flow data, we can initialize the internal state variables of the components by the phasor diagram calculation approach, which enables EMT initialization directly from the steady state.

Suppose that the power flow results of component \( g \) are \( V_g^{pf}, \theta_g^{pf}, P_{g}^{pf} \) and \( Q_{g}^{pf} \), which can be further expressed as

\[
\Delta V = V - V_0, \quad \Delta \theta = \theta - \theta_0
\]

port voltage \( \dot{V}_g^{pf} = V_g^{pf} \angle \theta_g^{pf} \) and injection power \( \dot{S}_g^{pf} = P_{g}^{pf} + jQ_{g}^{pf} \). Then, the current phasor is \( \dot{i}_g^{pf} = \left( \dot{S}_g^{pf} / \dot{V}_g^{pf} \right)^* \), and the phasors of other state variables (e.g. the transient potentials of synchronous generators) can be derived from the phasor diagram calculation [15]. Further, we calculate the instantaneous values of state variables at time \( t \) to compose the initialized snapshot at time \( t \). Taking current for example, the instantaneous current \( i_g(t) \) of component \( g \) can be differenced and represented as (6).

\[
i_g(t) = Gv_g(t) + Hv_g(t - \Delta t) + Jv_g(t - \Delta t)
\]

where \( v_g(t) \) is the instantaneous voltage, \( G \), \( H \), and \( J \) are the equivalent parameters determined by \( \Delta t \) and component parameters, and \( v_g(t - \Delta t) \) and \( v_g(t - \Delta t) \) are the historical voltage and current before \( \Delta t \), which can be represented by phasors as in (7)

\[
i_g(t - \Delta t) = \text{Re} \left( \dot{i}_g^{pf} e^{j\omega (t - \Delta t)} \right)
\]

Then, after the calculation of all instantaneous values of the state variables, we can derive the initialized snapshot of the AC main system, which the main system can be directly initialized from.

2) GRBC Subsystems. According to the definition in Section II, GRBC subsystems consist of RBCs and subsystems
with complex dynamics (e.g. HVDC systems), in which the initialized internal variables cannot be directly calculated from the power flow results. For RBCs, the reasons are the unavailability of the detailed models. For subsystems with complex dynamics, the amount of unknown variables is beyond that of the solving equations, and thus, it is also difficult to derive the initialized snapshot. To solve the aforementioned problem, a ramping approach with ideal sources is utilized to lead the EMT models of GRBCs to initialized snapshots.

For GRBC subsystem \( i \), to simulate the characteristics when this subsystem is connected to the main system, the Thevenin equivalent of the remaining system is required to ramp up the subsystem. In the simulation environment, the Thevenin equivalent can be derived from power flow data and a fault analysis at the boundary [16], as shown in Fig. 4.

We derive (8a) from Fig. 4(a) and (8b) from Fig. 4(b).

\[
\begin{align*}
\dot{E}_i^q &= \dot{I}_i^t Z_i^q + \dot{V}_i^b \quad &\text{(8a)} \\
\dot{E}_i^q &= \dot{I}_i^f Z_i^q \quad &\text{(8b)}
\end{align*}
\]

where \( \dot{E}_i^q \) is the Thevenin source, \( Z_i^q \) is the Thevenin impedance, \( \dot{V}_i^b \) and \( \dot{I}_i^t \) are the boundary voltage and current of steady-state operation, and \( \dot{I}_i^f \) is the fault current to ground. Combining (8a) and (8b), we have:

\[
Z_i^q = \dot{V}_i^b / (\dot{I}_i^b - \dot{I}_i^f) \quad &\text{(9)}
\]

Then, during the ramping process with Thevenin equivalent sources, GRBC subsystems reach their initialized snapshots.

**B. Snapshot Splicing**

After every subsystem attains the initialized snapshot, the snapshot splicing mechanism interconnects all subsystems in the simulation environment, splices the snapshots of each subsystem, and then completes the EMT initialization.

There are various approaches to technically realize the snapshot splicing. However, since each subsystem reaches the calculated initialized snapshot independently and non-simultaneously, there may exist deviations among the instantaneous values of the subsystems’ AC port variables caused by the phase differences of the variables, and the worst scenario is that two variables have opposite phases at splicing time. These splicing deviations will further result in splicing oscillations, and in some severe scenarios, the splicing oscillations will lead to initialization failures. Thus, one critical problem with respect to the splicing mechanism design is how to reduce or even eliminate the splicing deviations.

For the above problem, a splicing time adjustment approach is introduced to reduce the splicing deviations. Generally, it is supposed that the variables \( y_i \) of subsystem \( i \) with phase \( \varphi_i \) and \( y_j \) of subsystem \( j \) with phase \( \varphi_j \) need to be spliced. These two subsystems reach their initialized snapshots at times \( t_i \) and \( t_j \) respectively, and we suppose that \( t_i < t_j \). Obviously, the splicing deviation of instantaneous values \( |y_i(t_i) - y_j(t_j)| \) is supposed to be zero if:

\[
\varphi_i(t_i) = \varphi_j(t_j) \quad &\text{(10)}
\]

In this splicing time adjustment approach, we adjust the slower time \( t_j \), and we can select a splicing time \( t_j^{adj} \) for subsystem \( j \) to reduce the deviation. By (10), the adjusted splicing time \( t_j^{adj} \) can be derived from \( \min(t_i, t_j) \) subject to \( \varphi_i(t_i) = \varphi_j(t_j) \), which is equivalent to (11).

\[
t_j^{adj} - t_i = 2kT, \quad k \in \mathbb{Z} \quad &\text{(11)}
\]

where \( T \) is the period of the AC system. Then, with the adjusted splicing times for each subsystems, the entire system will efficiently complete the initialization process.

**V. CASE STUDY**

In this section, the accuracy and effectiveness of the proposed EMT-GIS are illustrated by a case study on a hybrid AC-DC system in China.

**A. System Description**

The topology of the hybrid AC-DC test system is shown in Fig. 5, which contains 490 buses in total. The full EMT model of the test system is built on the CloudPSS platform [12]. A ±400 kV bipolar 12-pulse LCC-HVDC system, which adopts the CIGRE HVDC model (white-box model), is connected to the receiving-end system Z1. Moreover, the wind turbines in Z1 adopt the GW models provided by the Goldwind company, which are black-box components because of the privacy protection of the control system. The DC buses and wind turbine buses are selected as boundary buses.

![Fig. 5. Topology of the hybrid AC-DC test system.](image)

We implement the proposed EMT-GIS in the CloudPSS platform and then test the initialization performance with EMT-GIS and the default zero-state initialization scheme [17] (default steady-state initialization scheme is not tested due to its inapplicability to DC systems). Simulation results are provided in the following subsection.

**B. Simulation Results**

The power flow results of the test system are solved by the IPF-JFNG(m) algorithm (not shown here due to space limitations), thus enabling the EMT-GIS.

The accuracy test results are shown in Fig. 6, where we select the DC voltage and AC current for the initialization test and the DC and AC voltages for the fault test. The whole system is directly initialized from the steady state by EMT-GIS with the setting time \( t = 1 \) s. As shown in Fig. 6(a1) and
In this paper, a general initialization scheme for EMT simulation (EMT-GIS) is proposed to effectively initialize the EMT model of large-scale hybrid AC-DC grids containing black-box components. An IFP-JFNG(m) algorithm is introduced to provide the power flow results for EMT-GIS, which addresses the power flow problem of black-box components and ensures the accuracy of initialization. Then, an initialized snapshot calculation-and-splicing mechanism is proposed to ensure the initialization efficiency. A case study on a hybrid AC-DC system in China is performed on the CloudPSS platform, and the simulation results validate the accuracy and effectiveness of the proposed EMT-GIS.

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The efficiency of EMT-GIS is then tested on the CloudPSS platform. With the simulation step size $\Delta t = 20\mu s$ (the CloudPSS can achieve smaller step size while the selected $20\mu s$ is small enough to accurately simulate the hybrid AC-DC system), the initialization time of the test system with EMT-GIS is approximately 3.0 s, while that with zero-state ramping initialization is approximately 44.7 s. Thus, EMT-GIS significantly improves the initialization efficiency.