Improving the Performance of a Power Hardware-In-the-Loop System by a New Interface Algorithm

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Abstract. Power Hardware-In-the-Loop (PHIL) is an efficient way to analysis and test electrical equipment which is introduced into power system. To improve the performance of a PHIL system, the feasibility of several interface algorithms for PHIL system are analyzed. And a new interface algorithm, which is based on the virtual impedance method (VIM), is proposed. Therefore, the proposed interface algorithm is compared and assessed with the current interface algorithms. Through the comparing and testing, the proposed interface algorithm is verified that it obtains a better overall performance than another.

Introduction

With a rapid development of smart grid technology, amount of the power electronic equipment connecting to power grid, such as distributed generation, micro-grid, electric vehicles and other new technologies, many new devices will be introduced into the future power system. How to test and analyze the new devices poses new challenges to the traditional simulation methods. Power Hardware-In-the-Loop (PHIL) simulation [1], which combines the electrical equipment under test (EUT) and digital simulation (DS), is capable of testing the actual power devices. As a new trend of a power system simulation technology, a PHIL simulation is of great research value and has a wide application prospect. PHIL simulations allow the prototype of a novel apparatus to be investigated in a virtual system under a wide range of realistic conditions repeatedly, safely, and economically.

The interface algorithm is an efficient way to improve the performance of a PHIL system. A HVDC simulation model has been established on RTDS according to [2], and through the analyze and testing, the transmission line mode (TLM)l interface algorithm has been recommend for PHIL system; An ideal transformer method (ITM) interface algorithm model is analyzed in [3]. The feasibility of a time-varying first order approximation method (TFA) has been analyzed[4]. Several interface algorithm models are compared on literature[5]. A damping impedance method (DIM) model has relatively good stability and accuracy. However, through the study of the current literatures, most of the current interface algorithms are poor in practicability or performance of the PHIL simulations[6].

To improve the performance of a PHIL system, the applicability of the different interface algorithms and their influences on the performance of a PHIL system are analyzed. And a new interface algorithm, which is based on a virtual impedance method, is proposed. Therefore, the proposed interface algorithm is compared and assessed with the current interface algorithms. Through the analysis and PHIL simulations, the proposed algorithm is confirmed that it achieves a better overall performance than another.

Modeling of a PHIL System

A PHIL model, which is based on the transfer function, is the most commonly used method to analysis the PHIL system. It contains the circuit model that set on the digital simulation (DS) side, a
model of the electrical equipment under the test (EUT) and the a power interface model, and a power interface (PI) part contains the disturbance factors of the PHIL system.

![Figure 1. A PHIL system.](image1)

To analysis the modeling method, taking the first order linear circuit model as an example, the block diagram of the equivalent PHIL system, which is based on the voltage type ideal transformer method (ITM) model, is set up as shown in Fig.1. The voltage source $V_I(s)$ is series with an impedance $Z_I(s)$ on DS. It can be equivalent to the voltage source $V_Z(s)$ is series with a load impedance $Z_L(s)$ on EUT. The equivalent model of PI is controlled by the voltage source $V'_I(s)$, and the output current of the measured device is used as feedback signal to control the controlled current $I_o(s)$, and $R_L$ is its infinite internal resistance. The digital signal and the analog signal are interacted, so the DA link is equivalent to $G_{DA}(s)$. Meanwhile, the equivalent transfer function is $G_p(s)$, and thus the PHIL model system can be obtained. The open loop transfer function $G_{OL}(s)$ of the system is described:

$$G_{OL}(s) = G_{in}(s)G_I(s)\frac{Z(s)}{Z_I(s)}$$  \hspace{1cm} (1)$$

The block diagram of a transfer function for PHIL system is shown in Fig. 2.

![Figure 2. A transfer function of a PHIL system.](image2)

An impedance model of a PHIL system can be study by analyzing the impedance characteristics of the system.

![Figure 3. A transfer function of a PHIL system.](image3)

The PI is based on the continuous small signal linear model under the control block diagram as shown in Fig.3. $G_C(s)$ is a power interface controller, $G_{DA}(s)$ is an equivalent conversion model, $K_C$ is an active damping capacitance current feedback coefficient, $K_{PWM}$ is the equivalent gain of the inverter, and $G_d(s)$ is a transfer function of the time delay equivalent model of a power interface.

$$G_C(s) = \frac{K_{PWM}G_2(s)G_{in}(s)G_I(s)}{L_s + K_{PWM}Z(s)G_I(s)K_{PWM}G_1(s)}$$ \hspace{1cm} (2)$$

According to Mason’s method, the equivalent control block diagram of the PHIL system is obtained in Fig.4

![Figure 4. An equivalent control block diagram.](image4)
The output voltage $U_s(s)$ can be equivalent as follow:

$$U_s(s) = G_o(s)G_m(s)G_s(s) - G_o(s)I_o(s) = U'_s(s) + Z_o(s)I_o(s)$$  \hspace{1cm} (4)

It is obtained by formula (3.4) that an equivalent PHIL system is divided into two parts, one part is the output voltage source $U'_s(s)$. Its output dynamic performance is mainly determined by the controller of a PI; The other part is the output of a PHIL system. The impedance $Z_o(s)$, which includes the delay part, the power interface controller and the output filter, is influenced the overall impedance characteristics of a PHIL system. Therefore, the equivalent circuit of a PHIL system is obtained, as shown in Fig.5.

**Stability Analysis**

According to the impedance PHIL model shown in Fig.4, the equivalent circuit is shown in Fig.6. The DS system and the PI are equivalent to an impedance $Z_c(s)$.

According to Kirchhoff’s method, the output current $I_o(s)$ and voltage source $U_s(s)$ can be obtained as follow:

$$i_o(s) = \frac{U_s(s)}{Z_o(s) + Z_c(s)}$$  \hspace{1cm} (5)

The further equivalent is shown as follow:

$$i_o(s) = \frac{U_s(s)}{Z_o(s) + 1} \frac{1}{1 + Z_o(s)/Z_c(s)}$$  \hspace{1cm} (6)

The voltage source $U_s(s)$ can be stable operated under open circuit condition, and a load $Z_o(s)$ has no right half plane pole, so the stability of PHIL system depends on:

$$H(s) = \frac{1}{1 + Z_o(s)/Z_c(s)}$$  \hspace{1cm} (7)

The transfer function $H(s)$ is represented as a closed loop system, as shown in Figure 7.

Therefore, the stability of a PHIL system is determined by the closed loop transfer function $H(s)$. A stability criterion of the classical control theory is introduced to evaluate the stability of the system. The criterion method can also be applied to nonlinear equipment simulations.

**A New Interface Algorithm**

In this paper, a new interface algorithm (Virtual Impedance Model, VIM) is proposed on a PHIL system. The main idea of a VIM interface algorithm is that compensates the disturbance in the
impedance model, which makes the equivalent output impedance of the system close to the impedance of an original circuit, to improve the performance of a PHIL system.

\[ U(s) = U_o(s) + Z_o(s) \cdot I_o(s) \]  

(8).

And the \( U_o(s) \) and \( Z_o(s) \) can be obtained based on the former analysis.

\[
\begin{align*}
U_o(s) &= \frac{K_{PWM} \cdot G_i(s) G_m(s) G_o(s) U_i(s)}{L_C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)} \\
Z_o(s) &= \frac{L_C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)}{L_C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)}
\end{align*}
\]

(9).

\[
Z_{eq}(s) = Z_c(s) + \frac{1}{L C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)}
\]

(10).

The output impedance model contains an interface part, delays and errors. To eliminate the amount of disturbance in the output impedance, a VIM interface algorithm is introduced.

\[
T_o(s) = 1 - \frac{K_{PWM} \cdot G_i(s) G_m(s) G_o(s)}{L_C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)}
\]

(11).

According to the circuit theorem, the output impedance \( Z_o(s) \) can be corrected and compensated by a series impedance. As shown in Figure10, the virtual impedance \( Z_v(s) \) is introduced in series with \( Z_o(s) \), and the compensated impedance \( Z_{eq}(s) \) can be obtained:

\[
Z_{eq}(s) = Z_o(s) + Z_v(s) = Z_{eq}(s)
\]

(12).

The \( T_o(s) \) simplification is equivalent as follow:

\[
T_o(s) = 1 - \frac{K_{PWM} \cdot G_i(s) G_m(s) G_o(s)}{L_C s^2 + C_o s^2 K_{PWM} k_i G_i(s) + K_{PWM} G_o(s) G_m(s)}
\]

(13).
The transfer function of a PHIL system with series impedance can be obtained based on the impedance model shown in Figure 10, which is shown in Figure 11(a) and Figure 11(b).

$$\frac{1}{Z_2(s)} U_o(s) Z_1(s) + Z_c(s) + U_s(s) + G_{PI}(s) \frac{1}{Z_o(s)}$$

Figure 11. The PHIL system structure.

The PHIL structure with the virtual impedance $Z_c(s)$ is added. Therefore, the equivalent expression of the equivalent transfer function compensation is expressed:

$$G_{eq}(s) = \frac{L_2 C_2 s^2 + C_2 s + K_{peg} \cdot k \cdot G_f(s) + K_{peg} \cdot G_c(s) G_f(s)}{L_2 C_2 s^2 + C_2 s + K_{peg} \cdot k \cdot G_f(s)}$$

(14)

Figure 12. The PHIL system on VIM model.

As shown in Figure 12, the impedance model $G_{VM}(s)$ is set on DS side, the current $I_2$ is fed to the DS by the measured device, and the current $I_1$ is a controlled current source of DS, which $R_i$ is parallel to the infinite impedance of the controlled current source, without changing the circuit structure, increasing the impedance value or other equipment, and comparing the other power interface algorithm, the VIM model has strong flexibility and it is simple established on the real-time digital simulation software.

Experimental Verification

A PHIL Platform

To verify the efficacy of a VIM interface algorithm, a PHIL platform is established, which is shown on Figure 13. The voltage source $U_i$ is 220V, $R_j$ and $L_j$ are impedance and resistance, which are series with the voltage source $U_s$ on the DS side, two parts are split into the DS and the EUT, based on the TLM model; The inductor $L_j$ is equivalent to the line impedance, which is split into the DS and the EUT, and a PI, which is based on back to back converter, is used for a PHIL platform. The Tables I and Tables II show the parameters of a PHIL system, and the digital simulation step is 50μs.
Stability Analyze

The TFA method is calculated based on the prediction data, thus this paper does not analyze and test the TFA method. For another interface algorithms, such as TLM, DIM, PCD and ITM, it has relatively good practicability and feasibility. Therefore, several interface algorithms and the VIM is used to analyze and compare the performance of a PHIL system.

Taking the first order circuit, which is shown in Figure 15, as an example, the power supply voltage $U_S$ is 220V. The power interface parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Filter Parameters</th>
<th>Controller</th>
<th>DC voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0$(mH)</td>
<td>$C_0$(μF)</td>
<td>$k_p$</td>
</tr>
<tr>
<td>0.2</td>
<td>60</td>
<td>5</td>
</tr>
</tbody>
</table>

Two different circuit impedance parameters are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R_1$(Ω)</th>
<th>$L_1$(mH)</th>
<th>$R_2$(Ω)</th>
<th>$L_2$(mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>4</td>
<td>40</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>Group 2</td>
<td>4</td>
<td>80</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

Figure 14 (a) shows the poles of a PHIL system based on the ITM method only exist in a group 1, and the system can be stable. Figure 14 (b) shows there is a positive real part of the system, and it is unstable. Because the impedance ratio, between the DS side and HUT, is greater than 1. As shown in Figure 15 and Figure 16, the poles of the simulation model based on the PCD, TLM DIM and VIM only have the negative real part, and the system can be stable.

Figure 17, Figure 18 and Figure 19 show that several interface algorithms can be stable under the current simulation parameters and circuit structures, the error voltage waveform between a PHIL system and an original system can be obtained. The better simulation accuracy of the PHIL system, based on the ITM, DIM and VIM, have been obtained. Therefore, the VIM have relatively stability, accuracy and feasibility overall the performance.
In this paper, a VIM interface algorithm method, which is proposed to enhance the performance of a PHIL system, is described. Meanwhile, several current interface algorithms are compared by modeling and testing of a PHIL system. Therefore, the VIM method can be feasible for various PHIL simulations involving different circuits. Furthermore, the performance of a PHIL system platform inclusive of a linear circuit, improving by using the VIM interface algorithm. The effectiveness of the proposed method has been confirmed by the PHIL experiments.
References


