The maximum value of $f_c$ can be derived by applying the Routh–Hurwitz stability criterion on the characteristics equation of the closed-loop system (Fig.6):

$$1 + G_{open-Loop}.G_{filter} = 0 \tag{14}$$

$$f_c < \frac{1}{\pi T_D(k-1)} \tag{15}$$

Fig.7 shows the bode diagram of the system for $k = 2$ and $T_D = 50\mu sec$ for three different cases of no filter, with filter $f_c = 6kHz$ kHz (maximum value), and $f_c = 3kHz$. As it can be concluded from the results, this approach is effective to improve the stability and it is easy to implement, however $f_c$ should be as high as possible to avoid a big delay on the feedback measured current. The order of the filter depends on the device under the test [25].

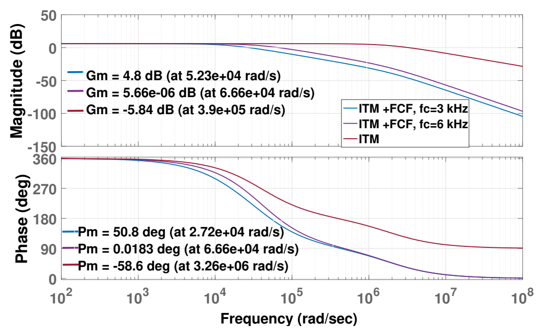


Fig. 7: Bode diagram of open loop system with FCF method.

*2) Hardware Inductance Addition (HIA) method:* Another approach to stabilize a PHIL simulation is to add an inductor $L_{ADD}$ in series with the DUT [18], [25], as shown in Fig.8. In this case, the open loop transfer function of the PHIL system can be obtained as:

$$G_{open-Loop} = \frac{Z_1}{sL_{ADD} + Z_2} G_{amp} e^{-sT_D} \tag{16}$$

With an assumption that the $Z_1$ and $Z_2$ are passive impedances, adding a certain value of $L$ can stabilize the system by increasing the Gain Margin (GM). The minimum value of $L$ can be derived by applying the Routh–Hurwitz stability criterion on the characteristics equation of the closed-loop system.

$$L_{ADD} > \frac{(Z_1 - Z_2)T_D}{2} \tag{17}$$

Fig.9 shows the stability region of the system for different values of $k$ and time delay. The stability performance of this method has been analyzed for $L = 25$ and $80\mu H$ (Fig.10). To meet the accuracy requirements, the additional inductance should be as small as possible, therefore this approach is applicable for small power rang of PHILs.

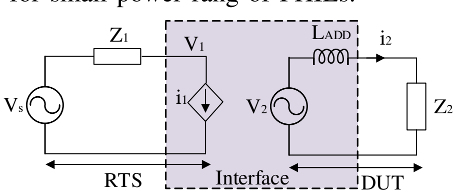


Fig. 8: Block diagram of ITM + HIA.

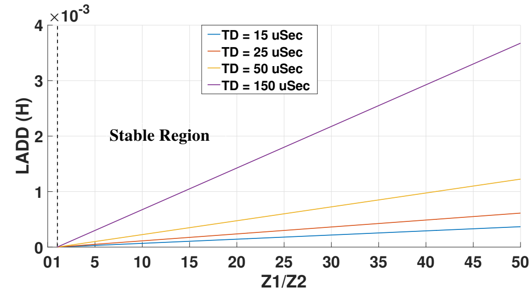


Fig. 9: Stability region of the PHIL for different L.

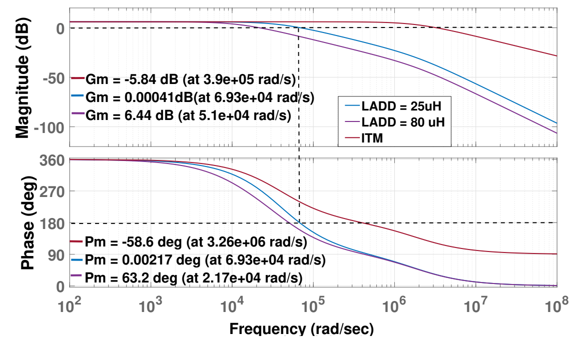


Fig. 10: Bode diagram of open loop system with HIA method.

*3) Multi-Rating (MR) Interface Method:* This method is based on partitioning the simulated system in the RTS into two subsystems. That part of simulation which is executed with slower time step is called "slow subsystem" and the other part with higher time step is called "fast subsystem". This approach takes advantage of modern high fidelity architecture of RTS systems which allow simulating some part of the system with higher sampling rate [25], [27]. Fig.11 shows the MR implementation of the system discussed in Fig.2, in which the simulated system in RTS is separated into two parts $(Z_1 = Z_{11} + Z_{12})$, where $Z_{11} = 1\Omega, Z_{12} = 1\Omega, T_D$ is equal to $50\mu sec$ for slow subsystem and $10\mu sec$ for fast subsystem. This implementation could improve the performance of the PHIL simulation by reducing both sampling time and impedance ratio at the interface with the DUT. When the ratio of time step in the slow subsystem to the fast subsystem is really high, the system is dynamically decoupled and can be separately analyzed for the stability. Therefore the stability is met when $Z_{12} < Z_2$ for the fast subsystem and $Z_{11} < Z_{12} + Z_2$ for the slow subsystem. Fig.12 shows bode diagram of the system with MR partitioning. It should be noted that this method could be combined with FCF approach and the value of the cut-off frequency will be higher than using FCF itself, resulting in better responses.

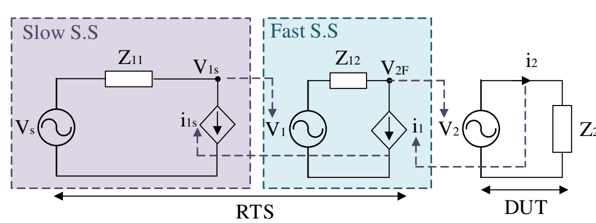


Fig. 11: Block diagram of ITM with MR partitioning.