In CM equivalent circuit, the resonance frequency, f_0, at 2.5 MHz were caused by the resonance of C_C with its parasitic element. While in the DM equivalent circuit, the peaks at 200 kHz and 2.5 MHz were caused by the resonance of C_{DL} and C_{CL} with its parasitic elements, respectively. At f_0, I_{CM} and I_{DM} were highly attenuated because most of the current flow through the parallel capacitors. There was also another peak at 1 MHz in DM equivalent circuit, where I_{DM} and the current in all parallel capacitors shot up. This was caused by the resonance between C_C and C_D.

Adding inductor, L_{GW} at the ground wire was intended to block I_{CM}. Fig. 6 shows that adding a ground wire inductor ($2L_{\mathrm{GW}}$ = 6.4 mH) increased the slope of the $\mathrm{IL_{CM}}$ increment (dotted blue line) at above 2 kHz. The way the ground wire is configured/mounted is critical as studied in [11]. It showed that with improper mounting configuration, the designed filter attenuation would be undermined.

IV. Source and Load Impedance Mismatch

Simulations were also performed for different sets of source and load impedances to illustrate a microgrid condition. The IL of PLF without and with ground wire inductor at different values of R_{S} and R_{L} are shown in Fig. 7 and Fig. 8, respectively. Using a fixed value of 50 Ω for R_{S} (R_{L}), a combination of 0.5, 5, 50, and 500 Ω of R_{L} (R_{S}) were simulated. There were 3 important parameters that influence the trend of IL, i.e. source and load impedance mismatch ($\alpha = R_{\mathrm{S}}/R_{\mathrm{L}} \neq 1$), total source and load impedance (R_{T}), and the frequency in which the influence of the previous parameters gave opposite effect (f_t). In this case, compared to a 50/50 Ω source and load impedances (R_{T} = 100 Ω), the trend of IL is summarized in Table II.

TABLE II. Insertion Loss Trend of PLF without Ground Wire Inductor under Different Source and Load Impedance Mismatch

		Higher R_{S}-R_{L} mismatch	**Lower R_{S}-R_{L} mismatch**
Above f_t	**R_{T} >100 Ω**	IL ↑	IL ↓
	R_{T} <100 Ω	IL ↓	IL ↑
Below f_t	**R_{T} >100 Ω**	IL ↓	IL ↑
	R_{T} <100 Ω	IL ↑	IL ↓

Compared to a relatively big grid, the source impedance (hence the total impedance) is expected to be higher in microgrids. Therefore, compared to 50/50 Ω source and load impedances, the attenuation at high frequency of a PLF without a ground wire inductor is expected to be higher if it is implemented in a microgrid. Higher impedance mismatch resulted in a higher IL and lower impedance mismatch resulted in a lower IL.

At a high impedance mismatch, there is a maximum value of IL that can be achieved. To simplify the analysis, using an ideal phi-shape filter equation as derived in [12], it showed $\mathrm{IL} \sim \frac{R_{\mathrm{S}}R_{\mathrm{L}}}{R_{\mathrm{S}}+R_{\mathrm{L}}}$, hence, the limit of maximum IL at above f_t can be estimated as in (2).

$$\lim_{R_{\mathrm{S}}\to\infty} \frac{R_{\mathrm{S}}R_{\mathrm{L}}}{R_{\mathrm{S}}+R_{\mathrm{L}}} \approx R_{\mathrm{L}} \tag{2}$$

It means that, including all nonideal characteristics, the maximum IL that can be achieved is limited by the value of R_{L}. Or in other words, at a certain R_{L}, there is a maximum IL regardless of how high the R_{S} is. Moreover, the value of f_t could be estimated, which is when condition (3) complies. R_{S} is the source impedance of reference PLF (in this case, 50 Ω) and R'_{S} is the actual microgrid source impedance.

$$\mathrm{IL}\left(R_{\mathrm{S}}, f_t\right) = \mathrm{IL}\left(R'_{\mathrm{S}}, f_t\right) \tag{3}$$

Fig. 7. Influence of source and load impedance mismatch to the insertion loss of the PLF without ground wire inductor

Fig. 8. Insertion loss comparison of PLF with different ground wire inductor under different source and load impedance mismatch

In the case of PLF with a ground wire inductor, the IL trend under different source and impedance mismatches showed a similar trend with PLF without a ground wire inductor at the frequency below f_t, as listed in Table III. There was a critical ground wire inductance value, where the IL showed the opposite trend, which was occurred at a very small value of L (in order of μH).

TABLE III. Insertion Loss Trend of PLF with Ground Wire Inductor under Different Source and Load Impedance Mismatch

	Higher R_{S}-R_{L} mismatch	**Lower R_{S}-R_{L} mismatch**
R_{T} >100 Ω	IL ↓	IL ↑
R_{T} <100 Ω	IL ↑	IL ↓

V. Discussion

The simulations show that the components' parasitic reduces the noise current suppression at high frequency, which is typically worse above the f_0 of the shunt capacitors. The f_0 is usually given in the component's datasheet, but it could also be calculated using (1) [10]. Having 2 or more parallel capacitors introduces an additional peak in between f_0, where the current suppression becomes low.

In microgrids, the system is most likely to have higher R_{S}, hence for a PLF without a ground wire inductor, a better IL and its maximum values at above f_t could be estimated. However, the presence of inductance in the ground wire could reverse the trend, in which IL becomes lower with higher R_{S}. This is most likely the case because this happened at a small value of ground wire inductance, which could be caused unintentionally, e.g. coiling ground wire.

Additionally, as studied in the previous works, a higher PEI switching frequency could also lower the PLF effectiveness. Nonideal inductor saturation curve should be taken into account because it is affected by the PEI switching frequency that is connected in the same system. A higher frequency current due to PEI high switching frequency results in a lower inductor's μ_r [13], hence lowers the inductance. Therefore, a higher switching frequency reduces the PLF effectiveness [7].

Lower PLF attenuation could be expected when it is implemented in a microgrid. Improving filter effectiveness by using bigger components was not always the best solution. It is better to carefully analyze the system's significant noise frequency to determine the required PLF response, hence, the use of a bigger L and C could be avoided. In many cases, it is difficult to identify the noise spectrum before everything is up and running. However, in a microgrid, the switching frequency of each PEI could be identified and used as a consideration for the initial design. This does not necessarily eliminate the need for tuning at the later design phase, but still could be used as a good starting point.

Moreover, PLF effectiveness could be improved by implementing a ground wire inductor, using higher μ_r core material for common mode choke, and implement a multi-section filter (adding another LC leg). With an additional LC leg, smaller components can be used. However, it has to be carefully chosen so it will not end up giving lower attenuation. To further improve filter effectiveness, bigger L and/or C could be used.

Arising drawbacks due to parasitic elements need to be considered. Higher L improved overall attenuation and broadened the frequency spectrum between f_0 of the inductor and capacitor, but it increased losses, cost, and weight. Higher C could improve attenuation at a lower frequency, but the f_0 was shifted to a lower frequency, which means the filter effectiveness upper-frequency limit was reduced.

VI. Conclusion and Recommendation

This paper observed the attenuation of PLF in microgrid applications, which was illustrated by source and impedance mismatch. The PLF is modeled in LTspice using approximated L and C component characteristics from the datasheet. There are 3 important parameters that influence the PLF attenuation trend, i.e. source and load impedance mismatch, total source and load impedance, and the frequency in which the influence of the previous parameters give the opposite effect.

In microgrid applications, the PLF is expected to exhibit lower attenuation due to high source and impedance mismatch, difficulties in implementing a proper filter grounding, and high switching frequency of connected PEI. Therefore, improvement should be made to achieve the desired attenuation. Improving PLF effectiveness should be done by first identifying the major potential noise frequency spectrum and consequently determine the components' size and configuration.

In microgrid applications, it is difficult to ensure the proper filter grounding. Therefore, special care has to be taken to make sure the most suitable yet possible grounding configuration is implemented to prevent undermining the designed filter effectiveness. Additionally, identifying the source and load impedances of a microgrid to estimate the trend of IL is useful for further tuning/modification of the PLF.

From this paper, the following are suggestions for future improvements and research.

- Detailed analysis on ground wire parasitics and influence of CM inductor saturation.
- Complete mathematical modeling of PLF insertion loss including parasitics elements.
- Identification and measurement of a complete filter parasitics.

References

[1] A. E. Shadare, M. N. O. Sadiku, and S. M. Musa, "Electromagnetic compatibility issues in critical smart grid infrastructure," *IEEE Electromagn. Compat. Mag.*, vol. 6, no. 4, pp. 63–70, 2017, doi: 10.1109/MEMC.0.8272283.

[2] R. Smolenski, M. Jarnut, G. Benysek, and A. Kempski, "Power electronics interfaces for low voltage distribution generation EMC issues," *2011 7th Int. Conf. Compat. Power Electron. CPE 2011 - Conf. Proc.*, pp. 107–112, 2011, doi: 10.1109/CPE.2011.5942216.

[3] M. A. Wibisono, N. Moonen, and F. Leferink, "Interference of LED Lamps on Narrowband Power Line Communication," *2020 IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity, EMCSI 2020*, pp. 219–221, 2020, doi: 10.1109/EMCSI38923.2020.9191485.

[4] F. das Guerra Fernandes Guerra and W. Santos Mota, "Current transformer model," *IEEE Trans. Power Deliv.*, vol. 22, no. 1, pp. 187–194, 2007, doi: 10.1109/TPWRD.2006.887092.

[5] F. Y. Shih, D. Y. Chen, Y. P. Wu, and Y. T. Chen, "A procedure for designing EMI filters for AC line applications," *IEEE Trans. Power Electron.*, vol. 11, no. 1, pp. 170–181, 1996, doi: 10.1109/63.484430.

[6] D. Nemashkalo, N. Moonen, and F. Leferink, "Practical Consideration on Power Line Filter Design and Implementation," *Proc. 2020 Int. Symp. Electromagn. Compat. - EMC Eur. EMC Eur. 2020*, 2020, doi: 10.1109/EMCEUROPE48519.2020.9245777.

[7] B. Zaidi, A. Videt, and N. Idir, "Influence of switching frequency and saturation of the magnetic material on the volume of common-mode inductors used in power converter EMI filters," *2017 IEEE Energy Convers. Congr. Expo. ECCE 2017*, vol. 2017-Janua, pp. 887–894, 2017, doi: 10.1109/ECCE.2017.8095879.

[8] L. Xing, M. Shen, M. Li, and W. Said, "Common mode choke optimization for three-phase motor drive systems," *2012 IEEE Energy Convers. Congr. Expo. ECCE 2012*, pp. 1399–1405, 2012, doi: 10.1109/ECCE.2012.6342651.

[9] J. Xue, F. Wang, X. Zhang, D. Boroyevich, and P. Mattavelli, "Design of output passive EMI filter in DC-fed motor drive," *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 634–640, 2012, doi: 10.1109/APEC.2012.6165885.

[10] C. R. Paul, *Introduction to Electromagnetic Compatibility (Wiley Series in Microwave and Optical Engineering)*. USA: Wiley-Interscience, 2006.

[11] N. Moonen, F. Buesink, and F. Leferink, "Unexpected poor performance of presumed high-quality power line filter, and how it improved," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2015-Sept, pp. 382–385, 2015, doi: 10.1109/ISEMC.2015.7256191.

[12] V. Tarateeraseth, "Derivation of Insertion Loss Equations for EMI Filter Design," *Fifth IASTED Asian Conf. Power Energy Syst.*, 2012, doi: 10.2316/P.2012.768-074.

[13] R. Grossinger, N. Mehboob, D. Suess, R. S. Turtelli, and M. Kriegisch, "An eddy-current model describing the frequency dependence of the coercivity of polycrystalline galfenol," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3076–3079, 2012, doi: 10.1109/TMAG.2012.2202097.