As a summary, it can be stated that the 2nd-order SOGI-LPFe has the benefits of having a better rejection to harmonic distortion and a less oscillatory behavior than the SOGI-FLL during transients. The rejection to harmonics increases with the harmonic frequency order. Therefore, the 2nd-order SOGI-LPFe can be an option for enhancing the performance of the existing SOGI-based structures.

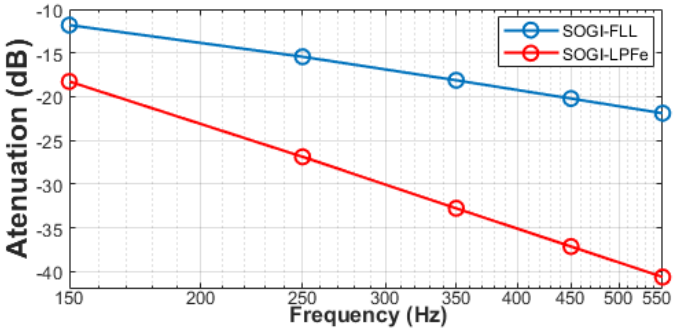

Fig. 16. Distortion amplitude in dB in the SOFI-FLL and the 2nd-order SOGI-LPFe estimated frequency for a grid voltage with harmonic distortion.

TABLE. II. PEAK-TO-PEAK AMPLITUDE DISTORTION IN THE ESTIMATED FREQUENCY FOR THE SOGI-FLL AND 2ND-ORDER SOGI-LFPe FOR DIFFERENT GRID HARMONICS ORDERS WITH 5% AMPLITUDE.

	3rd	**5th**	**7th**	**9th**	**11th**
SOGI-FLL	0.2567	0.1692	0.1241	0.0976	0.0804
SOGI-LPFe	0.1221	0.0453	0.0230	0.0139	0.0093
Reduction (dB)	-6.45	-11.45	-14.64	-16.93	-18.74
Reduction(%)	54.64	74.17	80.78	83.76	85.57

IV CONCLUSONS

In this paper a novel method for adaptively tuning the SOGI filter with the grid frequency is proposed. The method uses the estimated frequency obtained from the SOGI inner state variables and SOGI outputs plus a LPF for the proper tuning of the SOGI filter. This approach behaves identically to the normalized SOGI-FLL and presents the same small-signal linearized behavior around the rated grid frequency than the SOGI-FLL variant analyzed in [18]. Therefore, a second-order LPFe is proposed instead that behaves better than the SOGI-FLL during the grid frequency transitory perturbations and has a higher rejection to the harmonic distortion. The simulation results show that the proposed 2nd-order SOGI-LPFe has less oscillations and a smoother response than the SOGI-FLL at the event of a frequency step perturbation. Moreover, it has a higher rejection capability to harmonics than the SOGI-FLL. Therefore, it is concluded that the proposed system can be used to enhance the performance of any SOGI-based system.

REFERENCES

[1] A. Kusko, *Power quality in electrical systems*. McGraw Hill. 2007.

[2] B. Singh, A. Chandra, K. Al-Haddad, *Power quality: problems and mitigation techniques*. Wiley 2015.

[3] IEEE Standard 1547, "IEEE standard for interconnecting distributed resources with electric power systems," 2003.

[4] P. Roncero-Sanchez, X. del Toro Garcia, A. P. Torres, and V. Feliu, "Robust frequency-estimation method for distorted and imbalanced three-phase systems using discrete filters," *IEEE Trans. Power Elect.*, vol. 26, no. 4, pp. 1089-1101, Apr. 2011.

[5] J. Svensson, "Synchronization methods for grid-connected voltage source converters," *Proc. Inst. Electr. Eng. – Gener. Transm. Distrib.*, vol. 148, no. 3, pp. 229-235, May 2001.

[6] M. Karimi-Ghartemani and M.R. Iravani, "A method for synchronization of power electronic converters in polluted and variable-frequency environments," *IEEE Trans. Power Systems*, vol. 19, no. 3, pp. 1263-1270, Aug. 2004.

[7] F.D. Freijedo, J. Doval-Gandoy, O. López, and E. Acha, "Tuning of phase-locked loops for power converters under distorted utility conditions," *IEEE Trans. Ind. Appl.*, vol. 45, no. 6, pp. 2039-2047, Nov/Dec. 2009.

[8] N. Hoffmann, R. Lohde, M. Fischer, F.W. Fuchs, L. Asiminoaei, and P.B. Thogersen, "A review on fundamental grid-voltage detection methods under highly distorted conditions in distributed power-generation networks," *In proc. ECCE'11,* pp. 3045-3052, 2011.

[9] F. Gonzalez-Espin, E. Figueres, and G. Garcera, "An adaptive synchronous-reference-frame phase-locked loop for power quality improvement in a polluted utility grid," *IEEE Trans. Ind. Electron.*, vol. 59, no. 6, pp. 2718-2731, June 2012.

[10] S. Golestan, J.M. Guerrero, and J.C. Vasquez, "Single-phase PLLs: a review of recent advances," *IEEE Trans. Power Electronics*, vol. 32, no. 12, pp. 9013-9030, Dec. 2017.

[11] U. Nuβ, "Blindleistungskompensation mit selbsgeführtem stromrichter und kapazitivem energiespeicher," *Dissertation am elektrotechnischen institut der Universität Karlsruhe*, 1989.

[12] B. Burger and A. Engler, "Fast signal conditioning in single phase systems," *in Proc. EPE'01*, 2001.

[13] P. Rodriguez, A. Luna, M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "Advanced grid synchronization system for power converters under unbalanced and distorted operating conditions," *in Proc. IECON'06*, pp. 5173-5178, 2006.

[14] M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "A new single-phase PLL structure based on second order generalized integrator," *in Proc. PESC'06*, pp. 1-7, Jun. 2006.

[15] P. Rodriguez, A. Luna, I. Candela, R. Teodorescu, and F. Blaabjerg, "Grid synchronization of power converters using multiple second order generalized integrators," *in Proc. IECON'08*, pp. 755 – 760, 2008.

[16] P. Rodriguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 127-138, Jan. 2011.

[17] P. Rodriguez, A. Luna, I. Etxebarria, R. Teodorescu, and F. Blaabjerg, "A stationary reference frame grid synchronization system for three-phase grid-connected power converters under adverse grid conditions," *IEEE Trans. Ind. Electron.*, vol. 27, no. 1, pp. 99-112, Jan. 2012.

[18] S. Golestan, E. Ebrahimzadeh, and J.M. Guerrero, and J.C. Vasquez, "An adaptive resonant regulator for single-phase grid-tied VSCs," *IEEE Trans. Power Electronics*, vol. pp, no. 99, 2017.

[19] J. Matas, M.Castilla, L.G.Vicuna, J.Miret, E.Alarcón-G., and A.Camacho, "Fast grid synchronization technique based on a multiple cascaded general integrator scheme for distributed generation inverters," *in Proc. ISIE'12*, pp.1003-1010, Jun. 2012.

[20] J. Matas, M. Castilla, J. Miret, L.G. de Vicuna, and R. Guzman, "An adaptive prefiltering method to improve the speed/accuracy tradeoff of voltage sequence detection methods under adverse grid conditions," *IEEE Trans. Ind. Electron.*, vol. 61, no. 5, pp. 2139-2151, May 2014.

[21] J. Matas, H. Martin, J. de la Hoz, A. Abusorrah, Y.A. Al-Turki, M. Al-Hindawi, "A family of gradient descent grid frequency estimators for the SOGI filter," *IEEE Trans. Power Electronics*, vol. pp, no. 99, 2017.