Impact of Malicious Noise Attacks on Self-Synchronization of Communication-Free Inverters

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Abstract

Synchronous operation of inverters, devices that feed DC energy (e.g., from a photovoltaic source) to an AC load (e.g., grid), usually requires communication for synchronized coordination, making them vulnerable to cyber threats. Hence, recently, communication-free self-synchronizing inverters (CFSIs), based on virtual oscillator control (VOC) methodology (championed e.g., by National Renewable Energy Laboratory), have gained traction. Even though VOC-based CFSIs do not communicate with each other, they make local measurements. The impact of tampering with these measurements (i.e., noise injection/ attack) on the performance and synchronization of these CFSIs is an important issue. As such, this project explores and validates the impact of malicious noise attack on the synchronization of VOC based CFSIs.

Condition for Synchronization of Nonlinear Coupled Oscillators (COs) [1]

Network of N coupled identical nonlinear oscillators (Fig. 1) synchronize in the sense of (1)

$$\lim_{t\to\infty} v_j(t) - v_k(t) = 0, \quad \forall j,k = 1,\cdots N \quad (1)$$

where $v_j(t)$ is the output voltage of the j^{th} oscillator, if additional conditions in [1] are satisfied.

Further, it follows from Lienard's theorem [2] that an oscillator described by

$$\ddot{v} + r(v)\dot{v} + m(v) = 0 \quad (2)$$

has a unique and stable limit cycle if certain conditions outlined in [2] are satisfied. An electrical realization of (2) is shown in Fig. 1 for oscillator 1 which needs to satisfy $\omega_o = \frac{1}{\sqrt{LC}}$ (synchronizing frequency), $\epsilon = \sqrt{LC^{-1}}(\sigma - \frac{1}{R})$ is minimized (to realize a circular phase plane as illustrated in the attached figure), and $\sigma > \frac{1}{R}$.

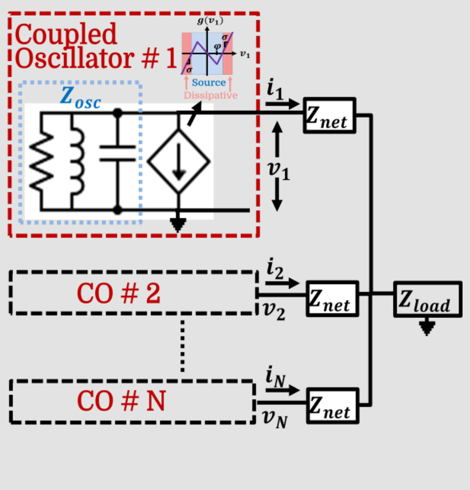
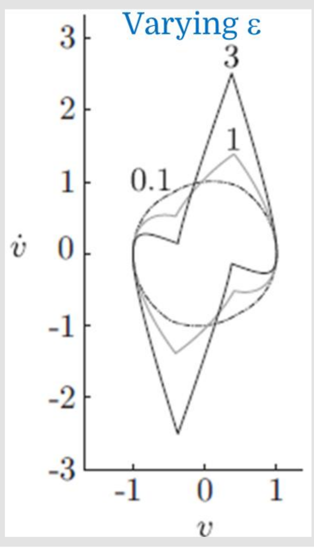


Fig. 1: Illustration of N-coupled oscillators feeding a load (Z_{load}) via network impedances (Z_{net}).



VOC based CFSI for Synchronized Coupled-Oscillator Realization [2]

To operate a network of (neutral-point-clamp or NPC) CFSIs like a network of coupled oscillators at 60 Hz, as illustrated in Fig. 1, each CFSI is controlled using a VOC, which is implemented in a digital (virtual) platform. However, unlike the coupled oscillator in Fig. 1, which powers the load directly, in Fig. 2, it is the CFSI that powers the load. As such, a scaled value of the current provided by a CFSI to the load is fed to the corresponding VOC to close the control loop. Injection of malicious noise in this feedback negatively affects the performance of the CFSI and the network.

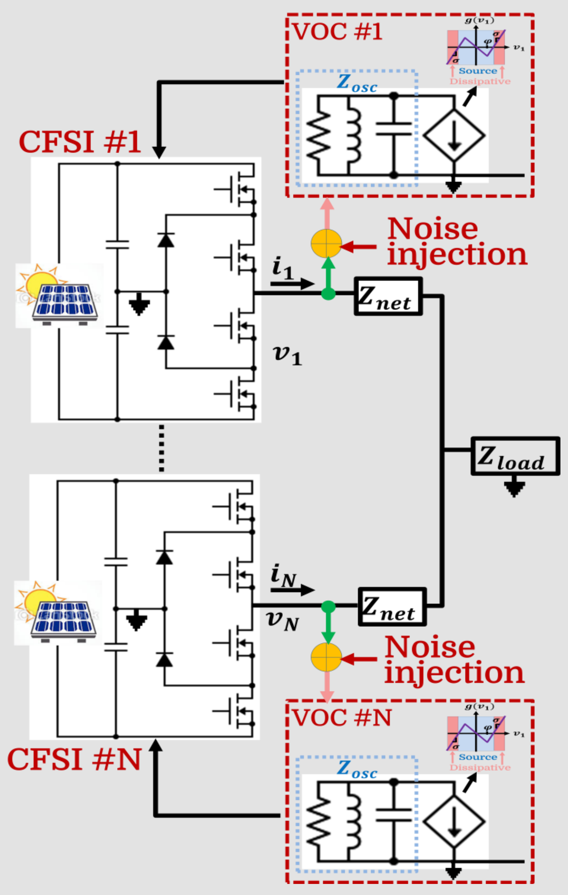
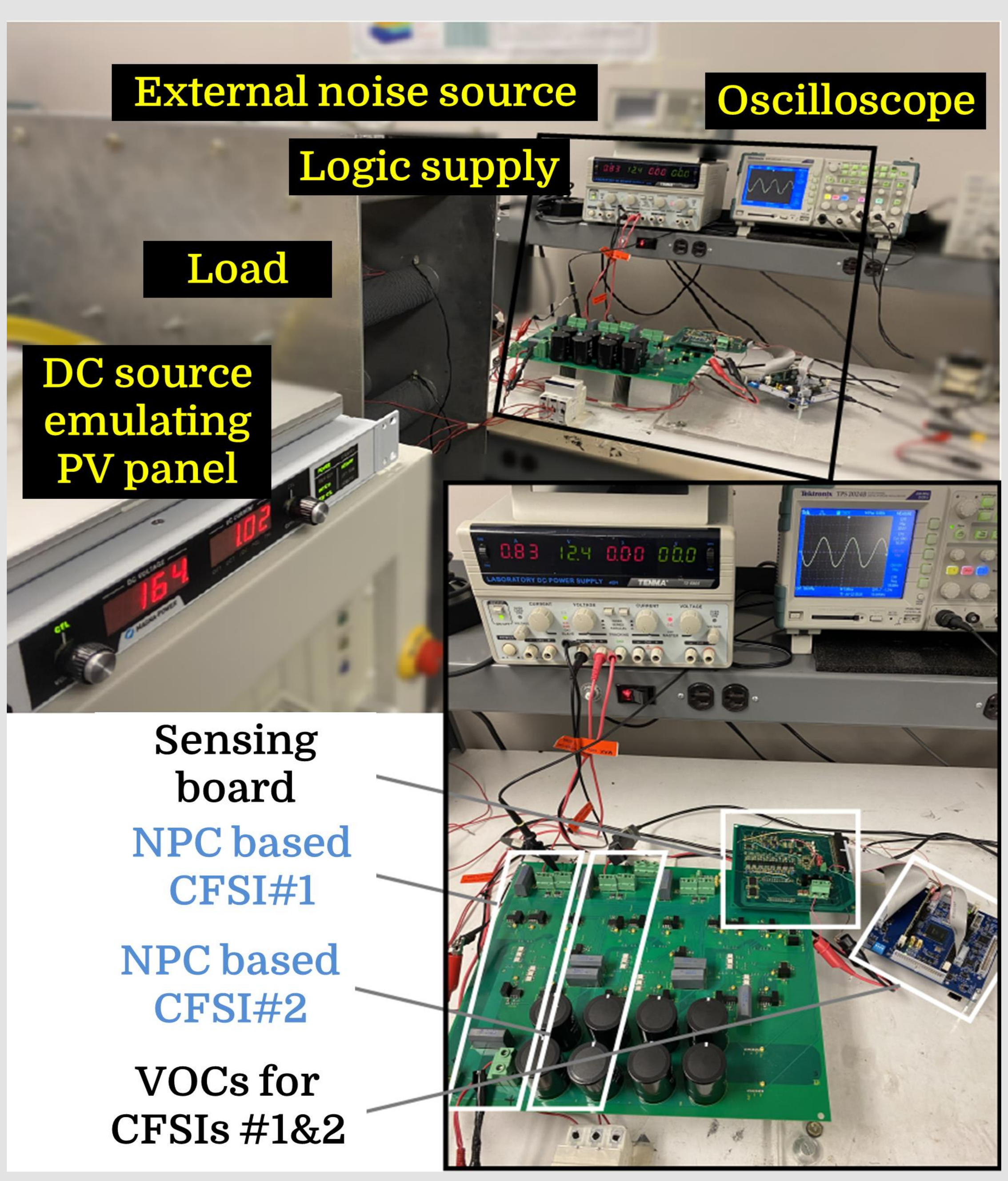


Fig. 2: VOC-based CFSIs operating as a coupled oscillator as in Fig. 1.

Experimental VOC-based CFSI Setup (Emulating Fig. 2) [2]



Key Experimental Parameters

Output AC voltage: 75V; Input DC voltage: 168 V; Z_{load}: 20 Ω; Load current (for each NPC-based CFSI): 3.75 A; (R, L, C) parameters of the VOC: 10 Ω, 500 μH, 14.07 mF; Scaling factors for load current and VOC output: 0.04 and 71; Z_{net} (R-L in series with the CFSI mid point and C in parallel to Z_{load}): 67 mΩ, 0.5 mH, 3.9 uF; and sampling and switching frequencies: 20 kHz.

Experimental Results [2]

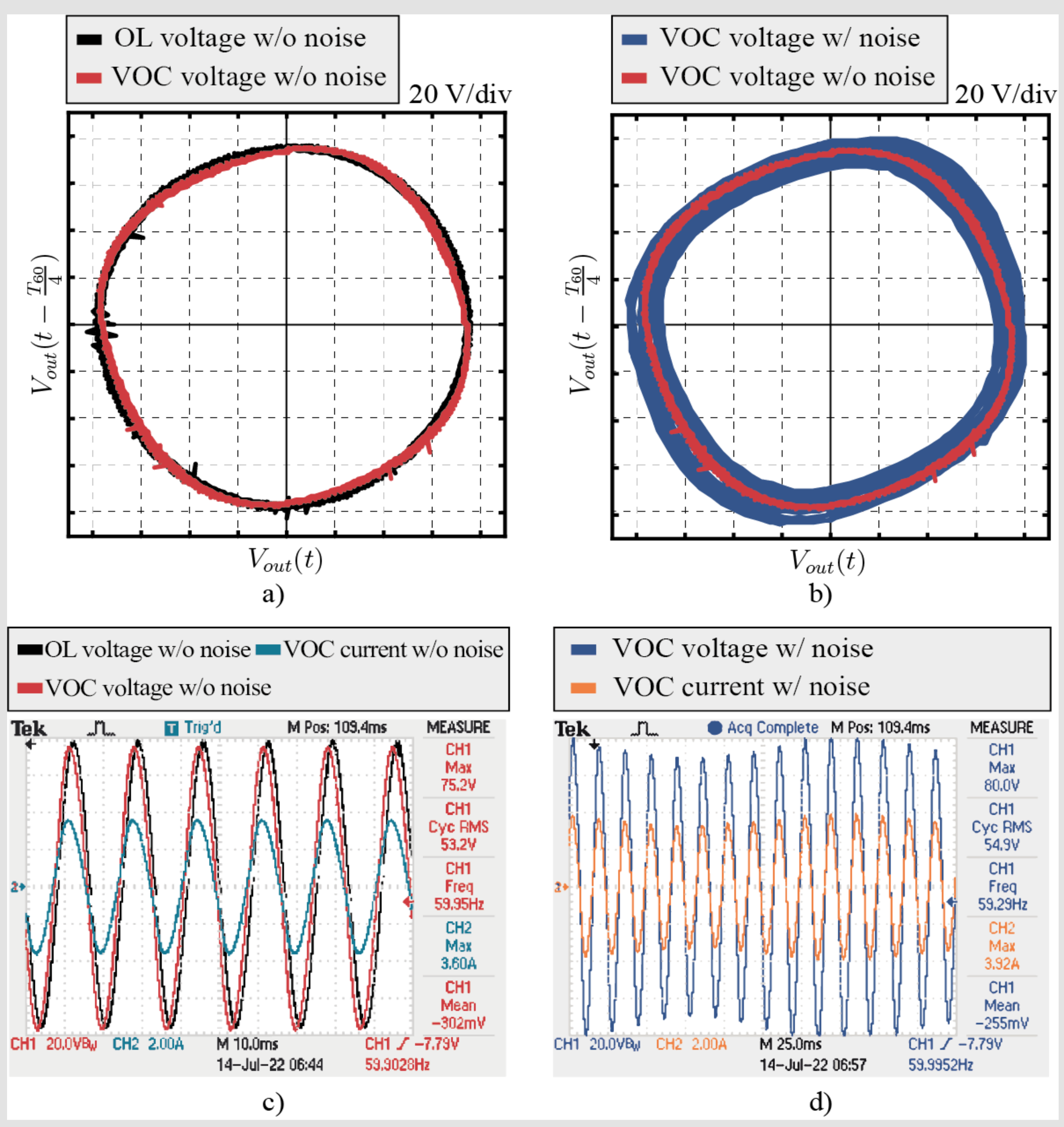


Fig. 3: Performance of a single CFSI: (a), (b) using phase-plane plots, and (c), (d) using time-domain plots. Noise is injected at 57 Hz to be within VOC bandwidth.

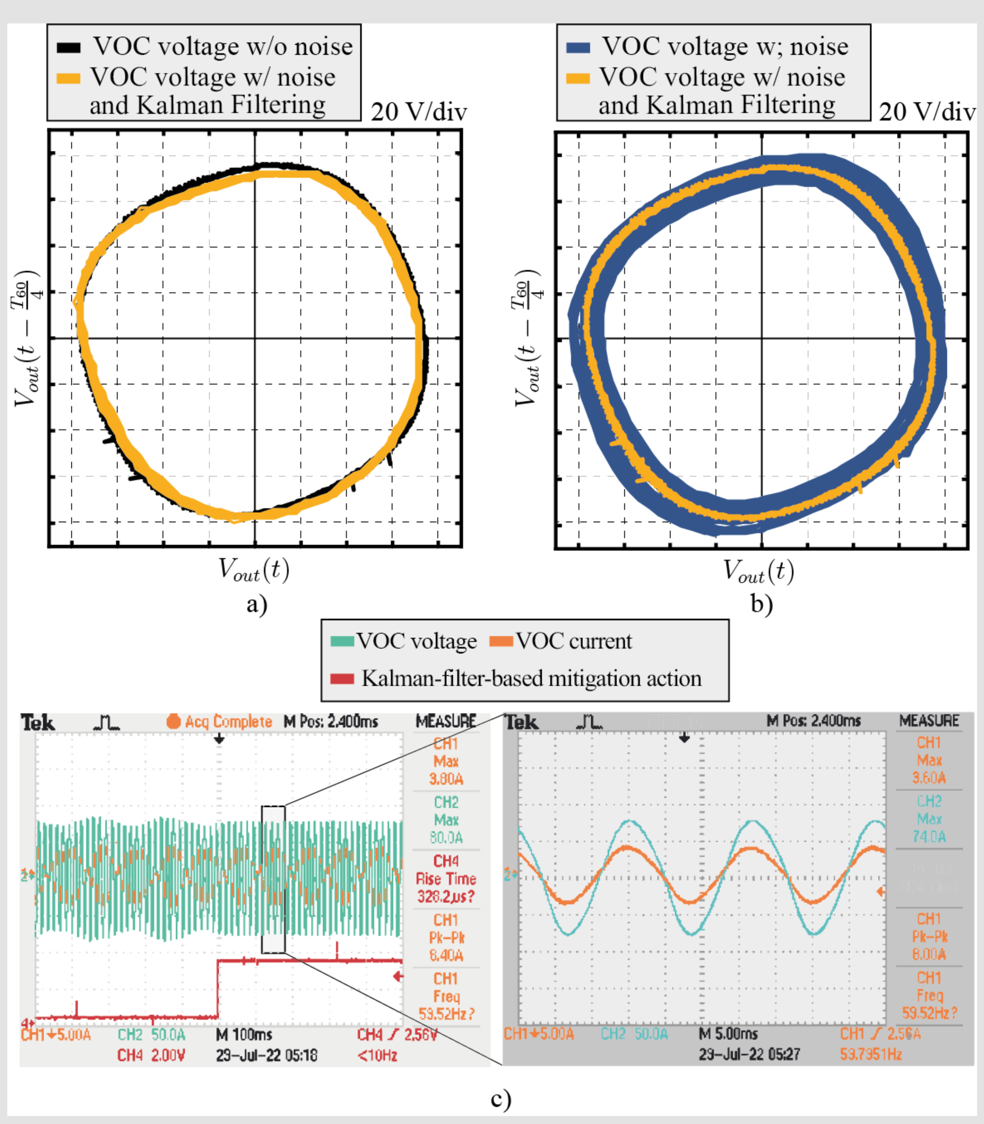


Fig. 4: (a) Mitigation of SNI in a single inverter: Performance of the VOC-based CFSI with and without Kalman- filtering-based estimation of i_1, which is tampered using a SNI at 57 Hz. (b) Closeness of the performance of the VOC-based CFSI using estimation to the nominal case when there is no SNI in i_1. (c) Time-domain performance demonstrates how activation of estimation stabilizes the CFSI dynamics.

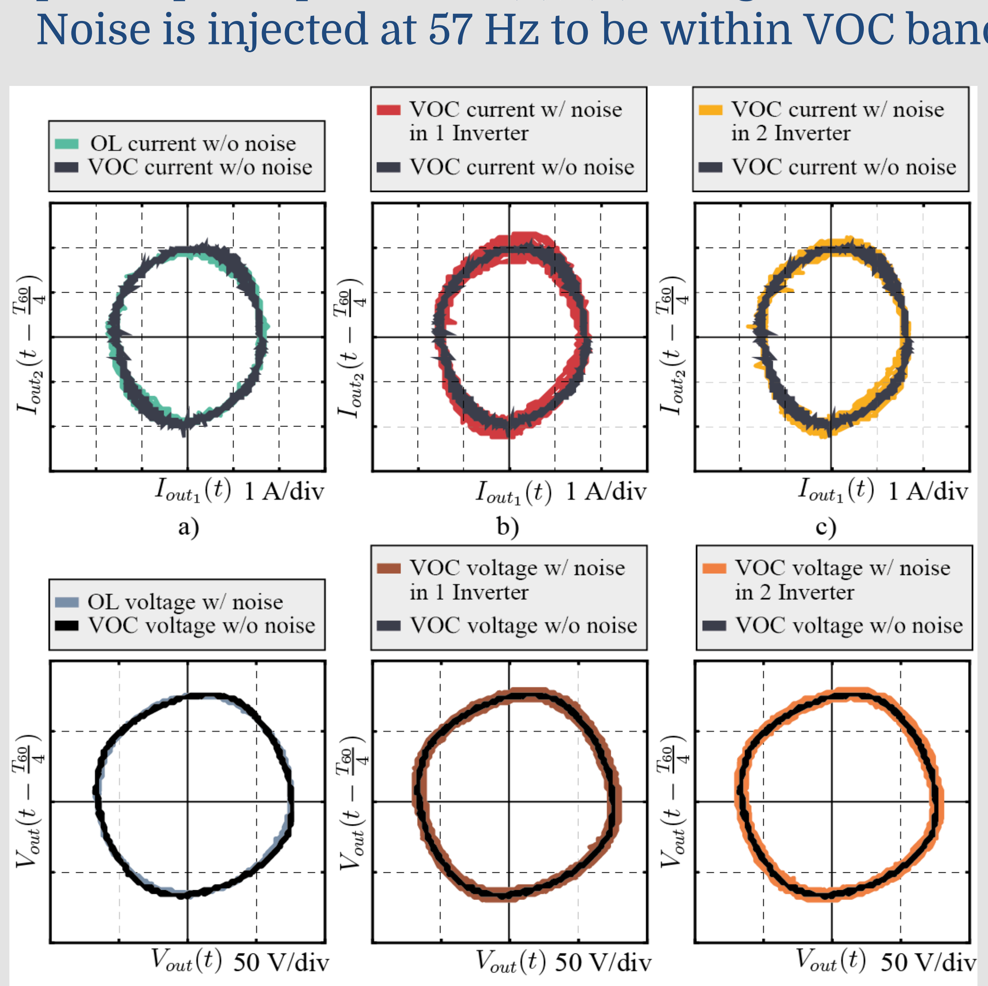


Fig. 5: Performance of 2 parallel (i.e., networked) CFSIs using phase-plane plots. Results in (b) and (e) demonstrate that noise injection at 57 Hz even in 1 CFSI, desynchronizes the network from the common 60-Hz output frequency. The results in (c) and (f) indicate that even if identical noise (above the Nyquist sampling frequency) is injected in the feedback of the 2 CFSIs, a minor difference in the sampling rates of the feedback creates a similar desynchronization problem.

Conclusions

While self-synchronizing VOC-based CFSIs nominally synchronize to a common output frequency (e.g., 60 Hz) without coordinated communication among themselves, which is an attractive feature, their global synchronization is vulnerable to noise injection in their local feedback(s). (Noise injection even in one CFSI can affect the synchronization of the overall CFSI network.) This happens because even though VOC-based CFSIs do not communicate over a data network they are coupled over the power network. Finally, a potential noise mitigation approach using the Kalman filter-based estimation method for a CFSI is discussed described and experimental results detailing the method's efficacy are provided, illustrating that the method of mitigation aids the VOC methodology in maintaining CFSI synchronization.

References

1. B. B. Johnson, "Control, analysis, and design of distributed inverter systems," Doctoral Dissertation, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 2013.
2. Sourojit K. Mazumder, M. Greidanus, J. Liu, and A. Mantooth, "Vulnerability of a VOC-based inverter due to noise injection and its mitigation", accepted and in press for publication, IEEE Transactions on Power Electronics, 2022.

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