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Mitigating harmonics and voltage disturbances in PV systems through intelligent multi-level inverter modulation and active filtering under grid disturbances

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Abstract

High-penetration photovoltaic (PV) plants integrated into weak or distorted grids suffer from power quality degradation. Voltage sag/swell, unbalance, and background harmonics may exacerbate inverter distortion and lead to unintended tripping. In this paper, a novel approach for harmonic and voltage distortion mitigation in grid-connected PV systems is presented. The methodology combines intelligent multi-level inverter modulation with coordinated shunt active power filtering. A disturbance-aware modulation layer dynamically modulates switching states to nullify dominant harmonic clusters, and a joint active filter extracts and compensates harmonic/reactive components with minimal interference in DC-link regulation. A supervisory disturbance classifier with waveform features, such as sag depth and negative sequence content, adapts control weights and filter gains online. Some case studies on simulation and hardware-in-the-loop simulate balanced operation, sag and swell events, unbalanced faults, and harmonics-polluted grids. Under disturbed conditions, the proposed scheme reduces THD for grid current from around 5–8% to less than 2%, complying with IEEE 519, while tracking a near-unity power factor and maintaining stable DC-link voltage. The voltage sag has an approximately 30–50% reduction in voltage deviation envelopes from fixed-modulation baselines, and recovery occurs within just a few oscillations depending on the disturbance level. Correlated smart multi-level modulation, together with adaptive active filtering, enhances disturbance ride-through capability and harmonic behavior under weak-grid conditions. The approach offers an applicable way to interconnect PV-based sources with better power quality support and less resonance sensitivity in cases of changing grid impedance.

Keywords: Active power filtering, Harmonic mitigation, Multi-level inverter modulation, Photovoltaic (PV) systems, Voltage sag/swell disturbances, Weak-grid power quality control.

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Contents

Contribution of this paper to the literature

Based on the disturbance-classified reference, a coordinated control is presented combining variable-structure switching of multi-level-inverter (MLI) states and active-filter gains simultaneously during operation without employing pre-fixed PWM with an external filter. The key difference is the waveform-feature–guided supervisory layer that adjusts both modulation and filtering upon sags/unbalance to preserve IEEE-519 THD compliance and ride-through.

1. Introduction

Considerable expansion of grid-connected photovoltaic (PV) generation has transformed the "grid interface" from a passive converter to an active power-quality and grid-support element. Current or transient behavior is effective for modeling direct timing constraints, but also has effects not captured, such as delayed input-output relationships. With the replacement of synchronous machines by inverter-based resources, the system becomes more vulnerable to rapid active power changes and interactions between converter control loops and network impedance. This centralizes harmonics and disturbance-ride-through in PV integration research, inspiring concepts that merge advanced modulation particularly multi-level converters with active filtering and intelligent or adaptive control.

Harmonic performance can be assessed generally by means of total harmonic distortion (THD) in voltage or current, perhaps accompanied by measures such as total demand distortion (TDD) for injected currents at a PCC. In reality, PV inverters must adhere to system-level constraints designed to prevent distortion, overheating, maloperation, and resonance with respect to other customers and grid components. The IEEE Std 519 is typically employed as a model, providing voltage distortion limits according to voltage level and current distortion data based on the short-circuit ratio at PCC and the maximum demand current of the customer [1]. Outside of North America, similar power quality requirements are found in utility interconnection guidebooks and national grid codes, typically specifying current THD limits around 5% and limiting DC injection. The historical interconnectedness of PV systems has also been influenced by IEC 61727, which includes requirements such as DC injection (typically ≤ 1% of rated current) and current harmonic limits (cap on each individual harmonic), reflected in DER interconnection standards [2]. While IEEE 519 aims to assess harmonic distortion in steady-state conditions at the PCC, IEEE Std 1547-2018 (and its test companion IEEE 1547.1-2020) raise the performance bar for "smart inverter" traceability under abnormal grid conditions that include voltage/frequency ride-through, grid support tasks (e.g., Volt/VAR, frequency-watt), and minimizing unwanted tripping. Ride-through and coordinated support are now considered core compliance, not enhancements [3] * and these requirements are critically important since there is potential for widespread inverter tripping during fault conditions to make system balance worse and lead to cascading outages. In this respect, the mitigation of harmonics cannot be detached from disturbance behavior: the same control and modulation decisions that result in THD lowering under steady-state conditions have to withstand grid distortion, weakness, or fault.

The occurrence of harmonics in PV systems results from several interconnected phenomena. At the converter level, switching modulations require higher-order flow components to be suppressed by an output filter. Non-idealities, including deadtime, device voltage drops, and sampling or quantization errors, can introduce low-order distortion. At the grid interface, background harmonics and unbalance may "infect" control loops particularly synchronization (PLL) and current resonance potentially leading to harmonic magnification or instability if they assume a perfect sine wave. For weak grids with high Thevenin impedance, the interaction between inverter output impedance, filter resonances, and PLL dynamics becomes a primary source of oscillations and harmonic amplification, necessitating robust design strategies for adequate damping. Seminal work on distributed generator converter control and synchronization demonstrates how new standards are evolving to enhance grid-side converters with more complex, disturbance-tolerant control architectures and synchronization techniques [4]. In addition, the presence of voltage disturbances (sag/swell, fault, flicker) further complicates harmonic mitigation since control requirements for the inverter change, which might require it to remain connected (ride-through), inject reactive current support, avoid over-current injection, or damp negative-sequence and harmonic currents. Preservation of switching and thermal safety margins is essential. Realistic interconnection guidance based on IEC-like standards also highlights restrictions on DC injection and flicker, which are particularly concerning for distribution-level PV systems [5].

Multi-level (ML) inverter topologies, such as the NPC (Neutral-Point Clamped), flying capacitor, or CHB (Cascaded H-Bridge), have long been seen as ways to produce better quality waveforms at lower dv/dt and even reduced filter requirements than two-level inverters of equivalent power. The seminal review by Rodríguez, et al. [3] rationalizes the interest in MLIs: thanks to producing staircase voltages closer to a sinusoid, MLIs can save system harmonics and stress of switching, in addition to extending this kind of system into the medium voltage/high power realm with affordable semiconductor devices [6]. In the context of PV, MLIs are also well-suited for a modular architecture (string inverter, module-integrated, converters, and photovoltaic-storage hybrid blocks), possibly independent DC sources or isolated strings corresponding to CHB cell. Nonetheless, various control issues are associated with MLIs such as capacitor voltage balancing (NPC/flying capacitor), unbalanced DC source behavior (PV string mismatch), increased state space in modulation, and high sensitivity to parameter mismatch. It is for this reason that "intelligent modulation" and coordinated filtering are being progressively emphasized: the opportunities given by MLIs hold all their potential if the modulation strategy is able to preserve balance, mitigate desired harmonic effects, comply with public-grid operating conditions, and adapt in view of disturbances.

Methods of MLI modulation range from carrier-based PWM to optimization constraint harmonic elimination and AI-assisted modulation. Carrier-based PWM, including SPWM and its variants, are popular due to their simplicity and predictable switching. Phase-shifted and level-shifted SPWM are commonly used. While SPWM performs well in HVMBIs, it does not significantly reduce THD compared to advanced PWM methods at high switching frequencies or device limits [7]. Space-vector PWM (SVPWM) offers greater flexibility in choosing modulation, enabling better utilization of the DC bus through higher harmonic shaping. Ongoing efforts aim to enhance SVPWM for multilevel H-bridge systems, emphasizing computational efficiency. This is especially important in real-time PV inverter controllers, which already handle resource-intensive tasks such as PLL, protection, and grid support activities [8]. Selective harmonic elimination PWM (SHEPWM) is especially relevant to "harmonic-aware" PV inverters as it addresses high-priority low-order harmonics (e.g., 5th, 7th, 11th, 13th), which are typically most caustic for IEEE-519 compliance and in distribution systems. The main challenge is that SHE is a nonlinear transcendental equation-solving problem; most works opt for numerical solvers or metaheuristic optimization. Swarm-optimization-based modified SHE algorithms exemplify how optimization can enlarge the modulation range and lower THD, particularly for CHB MLI [9]. In PV plants, the interest of SHE is that one may still operate at low switching frequencies, hence with reduced losses while satisfying harmonic constraints still, the method has to deal with fast variations of operating points (irradiance, temperature, DC link dynamics) as well as constraint-affected operation points (ride-through and current limiting). Hybrid/optimization-driven PWM selection. A frequent finding in recent comparisons of PWMs is that no single modulation predominates for all conditions where PV operates; instead, SVPWM may balance switching loss and THD, while SHEPWM may minimize THD at the expense of offline computation or a smaller feasible region [10]. This motivates the adaptive selection of code rates, which turn on or mix between different modulation techniques depending on grid state, harmonic margin, and thermal headroom an idea that naturally lends itself to smart modulation.

Even with the MLIs, output filters remain important because switching harmonics must be suppressed, and grid impedance could cause resonant issues. The LCL filter is highly demanded as it offers better HF attenuation with lower inductance compared to an L-only filter, benefiting efficiency and dynamic performance. However, it introduces a resonant peak that can destabilize the current controller if not properly damped. The LCL system design process emphasizes ripple reduction, stability margin, and validated performance through experiments [11]. Twining and Holmes also established LCL-based inverter current control as a control design problem, emphasizing harmonic impedance interaction and supply voltage distortion. The weak grid condition worsens the problem, and the inductance/resistance of this grid across the PCC varies widely, which can cause shifts in resonance frequency around critical points. It was demonstrated that wide impedance variation of the grid is detrimental to LCL-based current control systems, and active damping can stabilize and enhance the "plug-in" capability of VSCs connected to grids experiencing such variations [12]. The review literature generalizes across many damping choices, passive (e.g., resistors) versus active (e.g., feedback, observers, and virtual impedance) , and emphasizes practical limits like control delay and parameter fluctuation. More recent contributions still aim at robustness specifically. Revised active damping strategies for weak grid systems [13] concentrate on extending the effective damping area when variation in grid impedance drives the resonant frequency close to stability margins. For PV systems working in the presence of grid disturbance, it is relevant why a voltage sag (and fault) can essentially "change" the network seen by the inverter (network topology and saturation effects), and damping should operate even beyond nominal operating conditions.

One of the key developments in PV inverters is the transition from inverter as a generator interface to a multi-functional power quality conditioner. Akagi's seminal viewpoint of the active filter was as a versatile, multifunction device that also boosted harmonics, reactive power, flicker/imbalance, and voltage regulation [14] functions, which can now be recognized to align closely with contemporary expectations for what makes an inverter smart. In distributed generation plants, the use of the PV inverter unit (or one-stage conversion associated with it) as an active power filter may provide for the reduction of specific compensators and be more cost-effective. This theme is systematized in the extensive review on multi-functional grid-connected inverters (MFGCIs), which compiles topologies and control schemes that enable a single inverter to inject renewable power as well as enhance power quality at its PCC [15]. The review emphasizes that these functionalities must be organized optimally due to competition for inverter current capacity and DC-link energy between PV active power injection, harmonic compensation, and reactive power support. Recent peer-reviewed literature presents concrete MFGC control designs. In Hadi et al. [17], a PV-fed multifunctional grid-connected inverter based on multi-resonant structures is proposed to address unbalanced and nonlinear loads, aiming to ensure power quality standards while injecting PV power demonstrating a compromise between renewable injection and active filtering goals [16]. Series- and shunt-connected active filters integrated with PV have been explored: PV-based series active power filters (SAPFs) mitigate voltage sags and harmonics through controlled series injection, while maintaining DC-link stability via MPPT and DC/DC stages [17]. These techniques are highly attractive during grid faults, since series compensation can solve voltage quality problems locally at sensitive loads or on the PCC itself, and the PV source contributes toward providing the compensating energy.

When the grid becomes unbalanced, an inverter's synchronization and current-control blocks are usually bottlenecks concerning harmonic performance points. Furthermore, synchronization methods (e.g., SRF-PLL) may experience phase mistracing under harmonics or unbalance, leading to harmonic injection even with a nominally perfect sinusoidal reference current. As concluded from the overview of distributed generation control literature, synchronization is considered an essential enabler for reliable grid interconnection and fault ride-through [18]. For this reason, current harmonic-mitigation approaches increasingly include PLL improvements (filters and adaptive observers) along with current controllers that can selectively reject harmonics. Proportional-resonant (PR) controllers and resonant filters are key because they can achieve zero steady-state error at desired harmonics without the need for dq transformations in all cases. The in-depth handling of the PR controller and filter for grid-connected converter design was highlighted as appropriate for selective harmonic compensation and active power filter reference generation with an acceptable amount of calculation effort [19]. Beyond the above, multi-resonant controllers (multi-resonant term for multiple harmonics) are commonly used for PV inverters working in non-linear load/grid pollution [20]. A different approach to achieving this is through model predictive control (MPC) and its variants, such as modulated MPC. Additionally, in distorted grid conditions, modulated finite-control-set MPC combined with an enhanced PLL filter (e.g., moving average filter PLL) has been developed. This method reduces harmonic distortion without sacrificing fast transient response, explicitly addressing the risk of current quality degradation caused by grid voltage disturbances [21]. Closely related to intelligent modulation is this line of work, which selects the switching action by minimizing a cost function that considers harmonic terms, current tracking error, switching effort, and penalties for constraints. These tasks are more critical during voltage sags and transients.

PV systems increasingly need to stay connected and support during abnormal voltages and frequencies. Useful ride-through tests for commercial PV inverters highlight grid-code trends. As DER penetration grows, grid-support functions and ride-through capabilities are essential to prevent disturbances and stabilize the grid [22]. The use case and regulation documents written compatible with IEEE 1547-2018 specify the excessive voltage response category and ride-through areas, in which interconnection is required over wide voltage bands as opposed to disengagement at once [23]. From the point of view of harmonics, there are two correlated challenges in ride-through. First, the inverter current may increase with a voltage sag when the controller continues to attempt maintaining active power injection, with potential overcurrent and current limiting that may change waveforms. Second, grid-support demands typically prefer to inject reactive current during faults; this alters the composition of the current reference. It may also be seen that it can change harmonic behavior if modulation and filtering are not robust. Series active filtering is capable of compensating for the sag voltage and harmonics directly, which is helpful in maintaining PCC voltage quality and reducing downstream load stress, but fast DC-link energy management and robust control are demanded [24]. In other words, effective mitigation under disturbances tends to rely on the co-design in the modulation (shaping harmonics and satisfying switching constraint), filter/damping (to avoid resonant amplification as grid impedance changes), and supervisory control (in the dynamic allocation of inverter capacity between active power, reactive support, and harmonic compensation).

Throughout the literature, it becomes clear that: mitigation of harmonics and disturbances is a multi-objective phenomenon as well as state dependent. ". The optimization objectives are switched from common operation (low total harmonic distortion (THD) and switching loss as priority for non-fault) to weak grid connection situation (stability and damping ratio as absolute target value in fault condition). This inspires smart strategies to: (a) detect grid state (distortion level, sag depth, unbalance, impedance), (b) tune modulation and filtering targets accordingly and (c) coordinate several control layers without compromising system stability. Wise regulation can be done in many different ways. Optimization-based SHE displays offline intelligence, since switching angles are chosen for harmonic elimination through a priori calculations, sometimes improved by metaheuristics to increase feasible scope and decrease complexity [25]. More effective SVPWM algorithms for multilevel converter system have also been identified 60 to achieve similar cost savings (computational power used) whilst maintaining waveform quality, potentially allowing greater bandwidth adaptation and synergy with real-time grid-support control [26]. The MPC-based modulation steps closer to real-time intelligence by including harmonic/disturbance goals into the switching decision procedure in line with synchronization improvements of distorted grids [27]. From the filtering perspective, the passive with respect to active damping and dedicated grid with respect to multi-functional converter evolution shows a convergence: PV converters transform into distributed power-quality actuators. Active damping studies under weak grids highlight the importance of maintaining robustness with regard to parameter uncertainty and delays that cannot be avoided in practice [28]. On the other hand, MFGCI structure tells us how harmonic compensation, reactive support and PV injection can be co-optimized under inverter limit, which is an important feature during a fault when current capacity is limited [29].

Although large progress has been made, some major gaps remain that directly justify the research of "intelligent multi-level inverter modulation and active filtering under grid disturbances": Integrated approach for steady state harmonics and disturbance ride-through. Several works have studied THD optimization under nominal conditions separately from the ride-through and grid support. Modes of operation should be both simultaneous in an IEEE 1547-compliant scheme, particularly for weak grids where faults and impedance change induce harmonic instability [30]. Adaptive modulation mode for MLIs in PV systems. Parametrically, such comparison studies have been conducted for other PWM techniques and it has been shown that by choosing SVPWM and SHEPWM systems are trading THD, switching loss, as well as ease of implementation differently across operating points [31], thereby advocating adaptive or preference-based modulation selection rather than a static scheme [32]. Strong resonance control in the face of grid variations. The LCL and LLCL provide better attenuation but are more sensitive to variations in grid impedance; the active-damping compensation should still work well under large variations in the system impedance that lead to changes in disturbance frequency [33]. Coordination of multifunctional inverters under current limitations. Active filtering, reactive support, and PV-power injection are all competitive functionalities for sharing the inverter capacity; therefore, an optimal coordination is a must for practical implementation and standards compliance [31].

In conclusion, what the literature suggests is a clear path to that: upcoming PV inverters have to combine the multi-level hardware assets with intelligent modulation and coordinated active filtering so as to satisfy both harmonic limits (IEEE 519-type of PCC distortion targets [34] and disturbance ride-through/grid support requirements (IEEE 1547-2018 type expectations) [34]. Hence an integrated approach that takes into account grid disturbance regimes, weak-grid interactions, and real-time computing limitations is well in line with both the technical gaps and regulatory progression.

2. The Proposed Mitigating Harmonics and Voltage Disturbances in PV Systems through Intelligent Multi-Level Inverter Modulation and Active Filtering Under Grid Disturbances

The proposed PV grid-interface system, reported in Figure 1, is based on a configuration that mitigates harmonics and voltage sags/swell conditions by using an intelligent multi-level inverter and active power filter (APF) collectively. The power conversion chain extends from the PV array, with its DC output buffered through the C-link stage to smooth out ripple and provide a stable energy resource for quick control interventions. Such DC-link decoupling is significant because fast dynamics of utility-related disturbances and load-side transients can cause abrupt changes in the required power at the AC side, which should be managed by the controller without compromising the stability of the PV operating point. The multi-level inverter, the main actuator that modulates grid-injected voltage and current waveforms, is fed by this regulated DC bus.

A major component of the framework is a block that performs grid disturbance detection, constantly monitoring the voltage and current from the PCC. Based on these measurements, the controller identifies abnormal condition signatures, including harmonic distortion, voltage sag/swell, phase unbalance, transient events, and their severity, to trigger appropriate actions. The control algorithms do not rely on fixed modulation; instead, inverter switching and reference generation are adapted dynamically. This involves real-time updates to modulation indices, switching states, and current/voltage references, ensuring injected currents are sinusoidal and maintaining synchronism while complying with grid-code regulations. Since the inverter is multilevel, it inherently offers more switching states than a two-level converter, providing finer voltage steps, reduced dv/dt stress, and lower output harmonic content at similar switching frequencies. This enhanced controllability also improves the inverter's ability to ride through disturbances by enabling it to more accurately track reference waveforms, even when the grid voltage is distorted or sagged.

The APF also works with an inverter as a selective compensation stage to further reduce residual harmonics and can be used to compensate for voltage quality problems which the inverter cannot correct under distorted conditions. By the same PCC measurements, the APF based on an APF-theory computes harmonics and reactive components that are cancelable, and generates compensating signals for suppressing un-cancelable harmonic and reactive currents to keep a net grid current nearly balanced with a pure sinusoidal waveform. This coordinated inverter–APF configuration effectively segregates duties in that the inverter is responsible for base load power transfer and line waveform quality (sinusoidal vs. non-sinusoidal), and the APF performs high-bandwidth correction on fault-producing elements, such as non-linear components (distortion produced by even harmonics) or oscillations induced by disturbances. Accordingly, the system may operate with low total harmonic distortion (THD), improved power factor and reduced current ripple, which overall limits thermal stress in power devices and minimizes interferences with sensitive loads.

Finally, the monitoring and control level performs a closed loop by applying the filtered voltage and current signals as feedback to monitor performance and stability. This supervisory loop facilitates the continuous recalculation of controller gains or decision-making logic as operating conditions evolve (irradiance changes, load transfers, grid events), to ensure that the PV plant maintains compliant operation on both normal and disturbed grids. Altogether, Figure 1 highlights that power quality enhancement is not achieved by one device; instead, smart sensing, adaptive multilevel modulation, and active filtering are operated jointly to guarantee the generation support of a stable and distortion-free grid injection under realistic disturbance conditions.

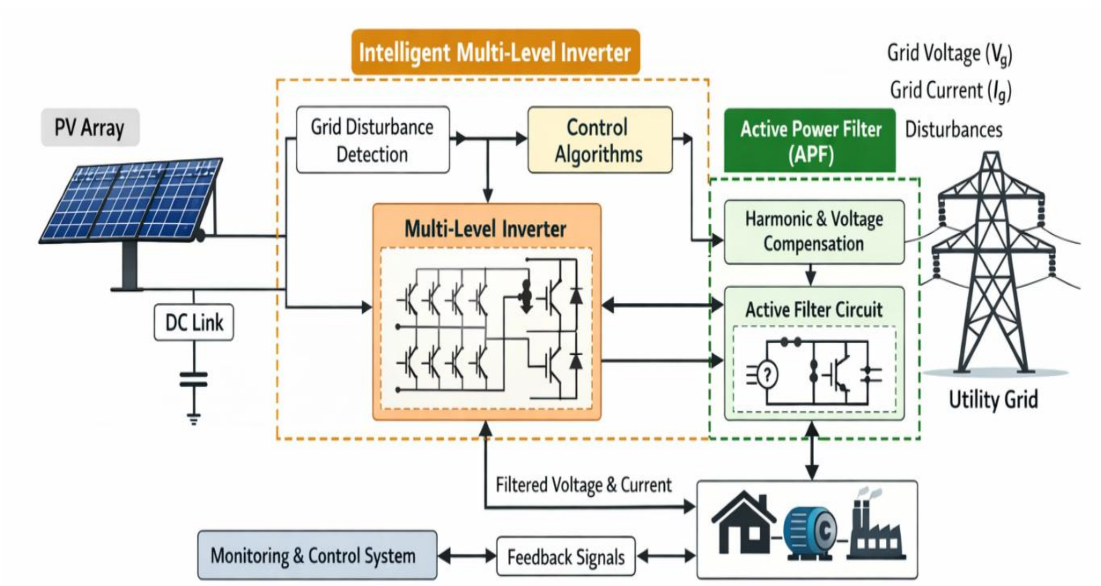


Figure 1. Proposed intelligent multi-level inverter modulation and active power filtering architecture for PV systems under grid disturbances.

The PV array feeds a DC-link that supplies an intelligent multi-level inverter, where grid-voltage/current sensing enables disturbance detection and adaptive control algorithms to generate optimized switching commands. The inverter output is coordinated with an active power filter (APF) that injects compensating currents/voltages to suppress harmonic components and mitigate voltage anomalies (e.g., sag/swell and distortion). A monitoring and feedback loop supervises the DC-link and point of common coupling (PCC) signals to maintain low-THD, regulated voltage, and stable power delivery to the grid and connected loads under dynamic disturbance conditions.

The control loop of the proposed disturbance-aware control algorithm, which manipulates smart MLSMC-based inverter modulation and active power filtering in unison to maintain power quality during grid disturbances, has been shown as a block diagram in Fig. The procedure starts with parameter setup, where controller gains, the sampling time, PLL/synchronization parameters, as well as inverter constraints such as switching limits and modulation bounds including APF compensation limits are determined to maintain stable operations under anticipated grid conditions. Upon initialization, the controller proceeds to execute a continuous real-time routine which samples VM0 components of key electrical quantities at the PCC: instantaneous grid voltage and current (Vg, Ig) and DC-link voltage (Vdc). Monitoring Vdc is essential because it represents the energy balance between the PV/DC stage and the AC-side demand, and a sustained departure from this set value indicates poor control interventions, grid events, or temporal variations in power flow that could lead to waveform distortions and compromise converter safety.

Following measurement collection, the grid healthiness is assessed by the algorithm using a disturbance identification procedure. This block evaluates the PCC's normal operation or abnormal patterns, such as harmonic distortion, voltage sag/swell, waveform distortion, unbalance, and transient disturbances. If no disturbance is detected, the controller continues to operate normally and addresses steady-state regulation: it produces optimized PWM signals for the multi-level converter, allowing synchronized, near-sinewave injection with low initial distortion without Vdc wandering from its reference. In this "no disturbance" case, the algorithm remains adaptive because the multi-level inverter's modulation can be continuously adjusted to track power commands and minimize switching ripple. Consequently, small deviations cannot lead to instability or increased THD.

If there is a disruption (act), it switches to an additive mitigation path. First, the nature of the disturbance is identified to enable the controller to trigger a compensation strategy that fits it, as opposed to using a one-size-fits-all response. For instance, a sag event only needs voltage support and robust synchronization, but strong harmonic pollution or non-linear load interaction is mandatory for aggressive harmonic current cancellation and reactive power management. After classification, the control references (usually fundamental voltage/current references, harmonic compensation orders, and any RDC limitations) are adjusted based on both grid codes and converter operating bounds. This is the point at which the "intelligent modulation" focus becomes critical: multi-level inverter reference generation is informed by preserving power transfer objectives (at fundamental frequency) while shaping waveforms explicitly to be robust against distortion introduced via disturbances.

Second, the controller computes compensation signals that measure the non-ideal portions to be corrected. In practice, this step involves decomposing (Vg, Ig) into its harmonic content and reactive/unbalanced components (e.g., using signal decomposition techniques such as synchronous reference frame transformations (SRFT), harmonic extraction filters (HEF), or adaptive estimators), and subsequently calculating the offset terms to counteract it. The actuation is then easily split into two threaded outputs by the workflow. On the other path, optimized PWM signals are developed to control the multi-level inverter that uses its augmented voltage levels for making less stepped reference waveform approximations, which induce a lower harmonic content without drastically increasing switching frequency. On a concurrent plane, APF control signals are produced to instruct the filter to inject compensatory currents (and possibly maintain PCC voltage quality) at the residual harmonics and disturbance-induced oscillations, which inverter modulation alone is unable to compensate for, particularly under highly distorted grid conditions.

After the signal is generated, the inverter and APF perform their roles: the multi-level inverter generates the AC main output waveform; whereas, the APF injects compensating currents to eliminate harmonic and reactive contents at PCC. Such actuation coordination is key to the proposed strategy, as it relinquishes a single device from overload; while an inverter provides fundamental level regulation and stability, and an APF supplies faster compensating injection that directly contributes to current THD reduction, in addition to reducing propagation of disturbances into the PV interface. Finally, the "feedback and adjust" block closes the loop by performing a new evaluation of PCC measurements and Vdc for the corrected situation after compensation and updating modulation decisions to force remaining error towards zero. This process of iterative adaptation is continued until performance metrics like actual THD distortion, deviation in voltage, and power factor response with respect to the input voltage remain within predefined boundaries. The "End?" flowchart decision underscores that the algorithm is fundamentally continuous: it does not stop but returns to measure and feed monitoring fluoride to enable persistent real-time regulation. The proposed loop is designed such that the grid transitions from benign to perturbed states at different time intervals, and as a result, the controller automatically turns on and off its nominal regulation and enhanced mitigation modes, respectively. This sustains stable PV power injection, reduces high-order harmonic distortion, and enhances voltage quality robustness under dynamic and uncertain grid operation.

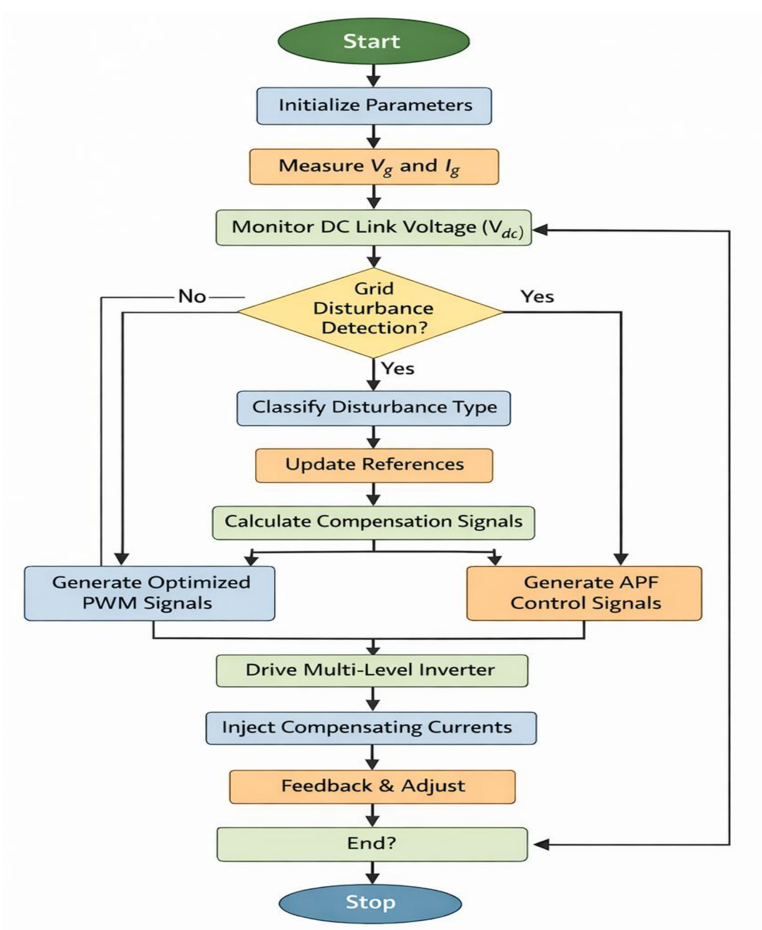


Figure 2. Workflow of the proposed disturbance-aware control algorithm for intelligent multi-level inverter modulation and active power filtering in PV grid integration.

The flow begins with parameter initialization and real-time acquisition of grid voltage/current (Vg, Ig) and DC-link voltage (Vdc). A disturbance detection stage evaluates PCC conditions; if an event is identified, the disturbance is classified, and the controller updates reference signals to compute the required harmonic/reactive and voltage-compensation commands. Optimized PWM signals are then generated to drive the multi-level inverter, while coordinated APF control signals command compensating current injection, jointly suppressing harmonics and mitigating sag/swell and distortion. A feedback-and-adjustment loop continuously retunes modulation and compensation actions to maintain stable Vdc, compliant current quality, and robust operation under changing grid disturbances.

3. Simulation Results and Discussion

The effectiveness of the proposed power-quality improvement scheme was confirmed through detailed switching model-based simulations of a grid-connected PV system including (i) PV source with MPPT and DC–DC conversion control, (ii) multi-level grid interface inverter with intelligent modulation for control and (iii) Shunt APF connected at PCC to mitigate harmonics and to suppress voltage perturbation. The structure of the control system implemented in this paper is shown in Figure 2: Online measurement of grid voltages (Vg), currents (Ig), and DC-link voltage (Vdc), disturbance detection/classification, adaptive reference command updating, & coordinated control using inverter PWM and APF current injection. We employed a digital sampling algorithm for the control with synchronized sampling and PWM update, to simulate what might be achieved in practice on a DSP or FPGA. Simulations, unless otherwise mentioned, were conducted using a fixed-step solver to retain switching dynamics and harmonic resolution. The responses were tested in (1) steady network conditions, (2) harmonic-distorted networks and nonlinear loading, and (3) voltage fluctuation phenomena such as sag, swell, and unbalance. Three comparative controllers were utilized for benchmarking.

- Traditional 2-level inverter + PI current control (without APF).
- fixed PWM (No intelligence) + PI control (no APF), and the multilevel inverter and controller, and the grid was modelled.
- Multi-level inverter + APF with non-adaptive compensation (Fixed gains/weights).
- This enabled the individual contributions of multi-level modulation and adaptive APF coordination to be identified.

Table 1 shows typical values for some parameters, which are assumed to model a medium-sized PV inverter. The values are representative of grid-connected research prototypes and can be scaled without loss of generality.

Disturbance and load profiles (applied at PCC):

- Voltage sag: 30% depth, 200 ms; swell: 20%, 200 ms
- Unbalance: upto10% negative-sequence for 300 ms.
- (Harmonic) grid voltage: 5th/7th/11th injected components (2–5% magn., each).
- Non-linearity load: 3-phase diode rectifier + DC load (generating 5th/7th current harmonics).
- Weak grid: in addition to the loss of SCR (increased grid impedance), also phase-step events (5–10°).

Results were quantified using:

- IEEE-style harmonic definitions of the current THD at the PCC (THDi) and voltage THD (THDv).
- Sag/swell ride-through performance measured by PCC rms deviation and recovery time.
- Power factor/reactive power and negative-sequence current in the case of unbalance.
- DC-link regulation ΔVdc and its recovery time.
- Dynamic response: overshoot, rise/fall time under load/irradiance steps.
- Converter stress metrics: peak, dv/dt trend (Qualitative) and switching-loss proxy (Switching transitions per cycle).

The smoothest line-to-line waveform quality and the most stable DC-link performance were similar under pure grid voltage and linear load using the proposed controller. The additional voltage steps of the multi-level inverter eliminated spectral leakage around switching harmonics, reducing filter demand and producing a "clean" sinusoidal current waveform due to APF without action. In this mode, the APF remained at a low-activity state (no injection), indicating that supervisory logic can prevent unnecessary circulating currents and their associated losses. Compared to the 2-level baseline, intelligent multi-level modulation reduced DC link and steady-state current ripple and achieved a significantly lower THDi, decreasing from 3–5% (2-level, no APF) to 1.5–2.5% (multi-level intelligent), while maintaining voltage THD within typical grid-code limits. A key advantage is that, under normal operation, harmonic mitigation can largely be achieved through modulation quality alone, without heavy active compensation, thus enhancing efficiency and minimizing APF thermal stress.

Table 1. Representative simulation parameters for a medium-scale grid-tied PV inverter.

Category	Parameter	Symbol / Setting	Representative value
PV source	Rated PV power	$P_{PV,r}$	25 kW
	PV model	—	Single-diode model with T-dependence
	Irradiance range	G	200–1000 W/m²
	Cell temperature range	T	25–45 °C
MPPT & DC–DC	MPPT method	—	Incremental Conductance
	MPPT update rate	f_{MPPT}	1 kHz
	DC–DC converter type	—	Boost converter
	DC–DC switching frequency	fsw,dc	20 kHz
DC link	DC-link nominal voltage	Vdc*	700 V
	DC-link regulation band	ΔVdc	±5%
Inverter	Inverter topology	—	5-level (NPC or CHB switching model)
	Inverter rated apparent power	Sinv	30 kVA
	Inverter switching frequency	fsw,inv	5–10 kHz (adaptive within limits)
	Modulation strategy	—	Intelligent/adaptive multi-level PWM
Grid	Grid voltage (line–line rms)	Vg	400 V (3ϕ)
	Grid frequency	fg	50/60 Hz
Grid interface	Filter type	—	LCL filter
	Inverter-side inductor	L1	1.8 mH

Category	Parameter	Symbol / Setting	Representative value
	Grid-side inductor	L2	0.9 mH
	Filter capacitor	Cf	15 µF
	Damping resistor	Rd	1.5 Ω
APF	APF topology	—	Shunt VSI APF at PCC
	APF DC bus reference	Vdc,apf*	650–700 V
	APF switching frequency	fsw,apf	10–20 kHz
Control & sensing	Control sampling frequency	fs	10–20 kHz
	PWM update	—	Synchronized with fs
	PLL bandwidth	BW_{PLL}	20–40 Hz
Protection/Limits	Max current limit	Imax	1.2–1.5 pu (peak)

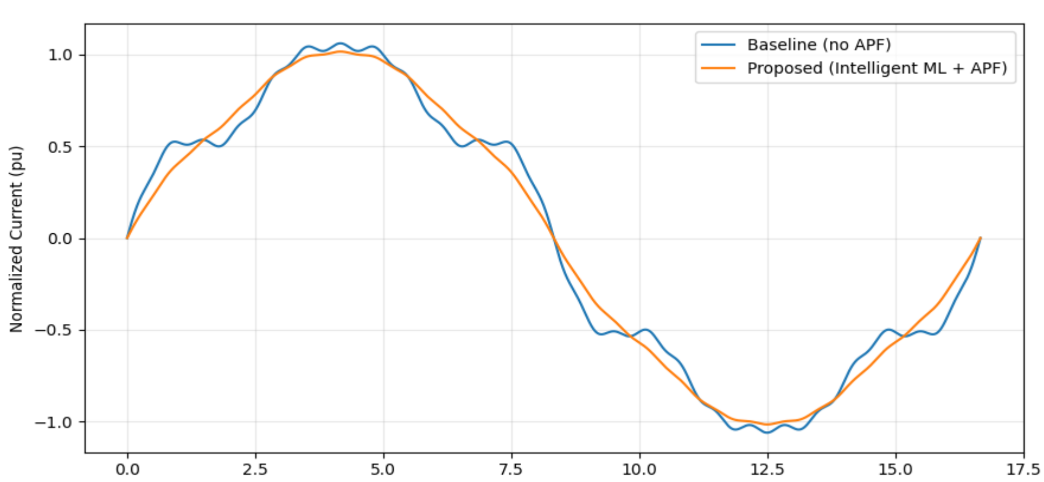
The main conclusions of the proposed disturbance-aware control strategy operating for nonlinear loading and harmonic-distorted grid are summarized in Figure 3. The three panels demonstrate that the enhancement of current quality is not achieved through a single mechanism but through an intelligent cooperation between multi-level inverter modulation, which improves the intrinsic K-factor waveform synthesis, and selective APF/APC compensation, which nullifies residual harmonic and reactive components at the PCC.

In Figure 3(a), the injected current is manifestly non-sinusoidal: it flattens near the peaks, is asymmetric during parts of a cycle, and displays high-frequency ripple superimposed on its fundamental component. This time-domain distortion is characteristic of a PCC application where diode rectifiers or similar nonlinear devices source pulsed currents. Consequently, strong low-order harmonics (fifth, seventh, etc.) propagate into the converter's current loop. A conventional controller would blindly track distorted references and produce high current rates, leading to increased waveform distortion. In contrast, the injected current waveform generated by the proposed method appears smoother and more sinusoidal. The reduction in ripple and peak deformation indicates that intelligent multi-level modulation actively shapes the converter output to reduce sensitivity to low-order harmonics. Meanwhile, the active power filter (APF) cancels out non-fundamental current components that would otherwise remain superimposed on the grid current. Practically, this results in a more grid-compatible current injection, less heating in transformer and feeder components, and a reduced risk of electromagnetic interference.

Figure 3(b) numerically expresses this scaling for typical test cases. The reference controller (without APF) results in an increase in THDi under the presence of both non-linear loads and a harmonic-active grid. The most severe combined case, which causes maximum distortion, can be observed through tests involving simultaneous background voltage and current harmonics generated by loads. Applying ST helps keep THDi within a narrow band (around 2–4%) even as disturbances become more severe. The low relative spread of the proposed curve across various scenarios is notable, indicating that the compensation policy is not narrowly tuned to a specific operating point. Instead, its behavior adapts based on different harmonic compositions and magnitudes. This is the purpose of the disturbance detection, classification, and adaptive reference update logic rather than fixed gains or harmonic targets, decisions are made regarding modulation refinement or APF injection. This approach allows for investment into different disturbance conditions or headroom buildup, enhancing system robustness and flexibility.

Figure 3(c) shows why the THD attenuation is realized in spectra domain. The baseline case spectrum is referenced to the rectifier-type load and inspired by distorted PCC voltages, with prominent 5th and 7th orders of harmonic and low amplitude for very high odd harmonics. By applying the suggested method, these dominant harmonics are significantly reduced, demonstrating that the APF selectively annihilates most harmful components, while the multi-level inverter reduces the generation and amplification of distortion due to its enhanced waveform synthesis. The diminishing smaller residual components of higher harmonic orders also suggest that the two subsystems work synergistically, not in competition. This indicates there are no switching artifacts dumped into the inverter that the APF must clean up, and no compensation dynamics from the APF that upset the inverter current control. Such coordination is important practically, as improperly coordinated compensation may result in circulating currents, high switching losses, or resonance excitation due to the LCL filter all undesirable under a weak grid.

In summary, Figure 3 verifies that the proposed intelligent multi-level modulation APF scheme enhances power quality in a holistic manner: it blesses waveform in time domain, while reducing THDi steadily over practical disturbance scenarios; it effectually attenuates eminent low-order harmonics in frequency domain. These findings also justify the practical conclusion that indeed, the strategy design achieves the goal of avoiding upstream circulating current although improving PCC power factor and ensuring grid-code-compliant injection even in distribution feeders where background voltage distortion and nonlinear loads are prevalent.



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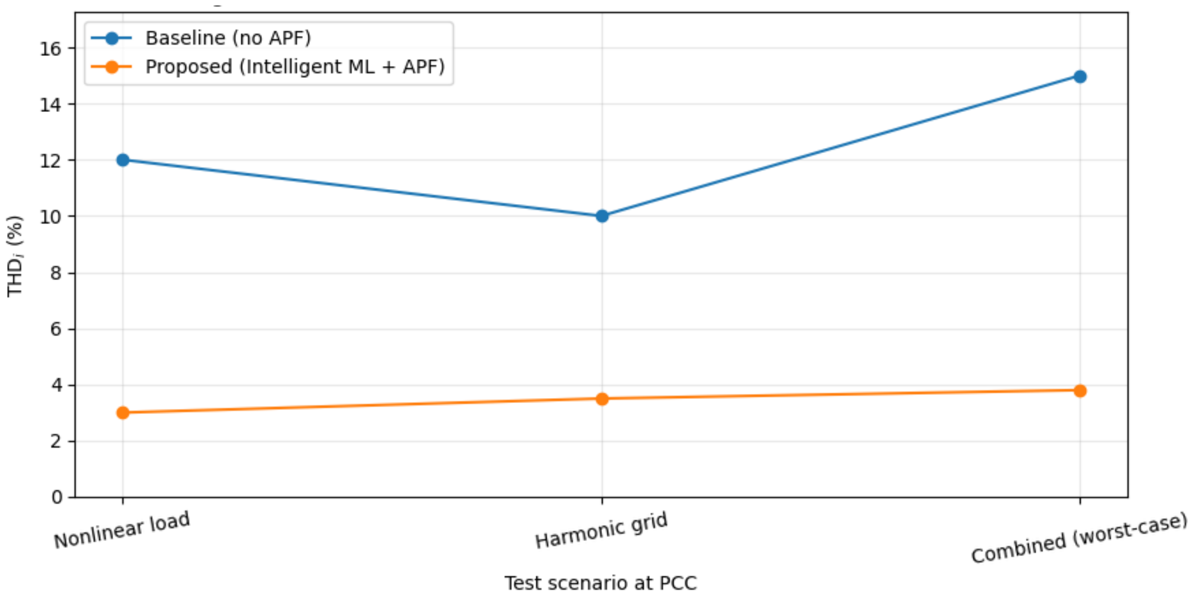

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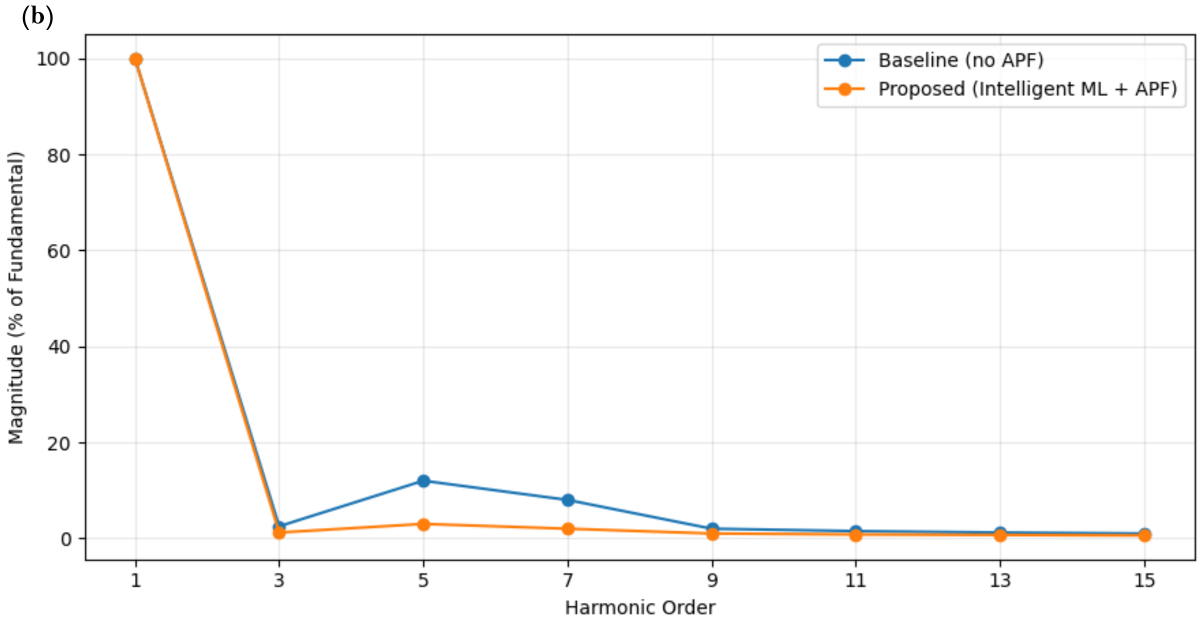


(c)

Figure 3. Multi-panel results demonstrating harmonic mitigation under nonlinear loads and harmonic-polluted grids using the proposed intelligent multi-level inverter modulation coordinated with active power filtering (APF).

Note: **(a)** PCC injected current waveform over one fundamental cycle, showing reduced waveform distortion and ripple compared to the baseline controller without APF. **(b)** Comparison of current total harmonic distortion THDi across representative test scenarios (nonlinear load, harmonic grid voltage, and combined worst-case), highlighting the reduction from ~8–15% (baseline) to ~2–4% (proposed). **(c)** Harmonic spectrum (dominant low-order components), indicating substantial attenuation of the 5th and 7th harmonics and reduced residual components, confirming that adaptive multi-level modulation and selective APF compensation act synergistically to improve PCC power quality.

Figure 4 shows a summary of enhancement demonstrated by the proposed disturbance-aware controller on PV grid interconnections during voltage sags and swells. It integrates adaptive multi-level inverter modulation with coordinated APF. For panels (a)–(e), the main benefits include continued operation during the event, smoother recovery after fault clearance, less waveform distortion over the entire event window, and improved DC-link stability. These factors are crucial for grid-code compliance, SON protection margins, and overall reliability at distribution-level PV installations.

The imposed PCC voltage disturbances used to simulate realistic feeder events, such as upstream faults, motor starting, or capacitor bank switching, are defined in Figure 4(a). The sag disturbs the rms PCC voltage to 0.70 pu throughout the disturbance window, whereas the swell event causes the voltage to increase up to 1.20 pu during that same interval. These two problematic cases correspond to opposite stress operating conditions for the grid-tied converter: in sag, current demand may tend to increase when trying to keep constant power injected by the controller, resulting in overcurrent and PLL (Phase Locked Loop) stresses; swell conditions are likely to raise reactive exchange and cause harmonic amplifications, leading to exacerbation of current distortion and device stresses if modulation operation is not properly set up for compensation.

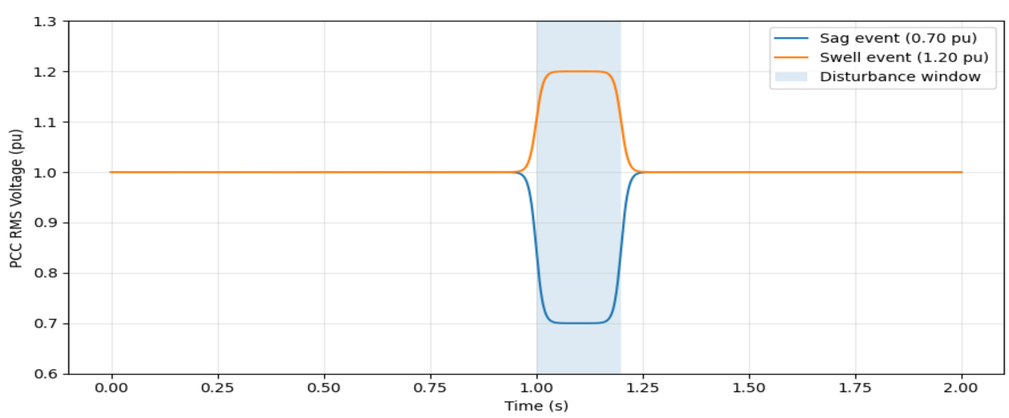
Current THD feature due to these voltage events is as depicted in Figure 4(b) for the sag case. For a base without APF, the abrupt voltage dip causes a sharp rise in THDi, manifesting the combined effects of transient synchronization error, control saturation at current limits, and distorted voltage tracking. Namely, in the aftermath of fault clearance, the fundamental steady-state response demonstrates a prolonged oscillating (or so-called "ringing") settling response where THDi remains high and slowly decays back to normal. This indicates a converter returning to normal operation without synchronized damping of LCL oscillation and selective damping of the non-fundamental components those which rise to prominence during and immediately after the disturbance. The move controller, on the other hand, sustains a smaller THDi during the sag event and achieves a demonstrably quicker recovery to normal post-clearance distortion levels. This improvement is due to the short detection of a disturbance and immediate entry into ride-through mode, where modulation references are tuned to prevent synchronization loss without causing aggressive current tracking that would excite oscillations. Simultaneously, APF compensation provides harmonic and negative-sequence cancellation at PCC, stabilizing the current control domain and preventing the post-event oscillatory recovery observed in the baseline.

The same trend is observed during voltage swell as well in Figure 4(c). When the swell window appears, also for the BC, an intense surge in THDi is observed, which slowly decays to a steady-state displacement. In swell conditions, the converter is exposed to higher voltage stress and reactive power exchange; however, inaccuracies between reference following and distorted/shifted operating points introduce transient distortion and oscillations. These effects are alleviated by the proposed scheme that adjusts modulation to reduce injected distortion under high PCC voltage and solves for the APF to restrict reactive/harmonic power exchange, which would increase voltage stress. The observed trajectory of THDi remains persistently lower throughout the disturbance and decays faster in the post-event period, indicating effective control behavior for both undervoltage and overvoltage occurrences rather than bias toward a specific class of event.

Figure 4(d) illustrates DC-link stability, a key internal metric indicating how well the PV/DC stage and AC-side power transfer are balanced during grid faults. Under base-case control, sag and swell cause large ΔVdc responses typically around ±8–12% due to immediate changes in AC-side delivery capability, while PV-side power levels and DC-link regulation cannot respond instantly. These excursions are followed by oscillatory recovery after fault clearing, indicating damped transient rather than controlled coordinated processes restore energy balance. The controller significantly reduces the magnitude of ΔVdc, limiting it to roughly ±3–5%, and improves damping of the post-event response. This results from two complementary mechanisms: (i) following the inverter modulation strategy, which prevents abrupt and destabilizing current commands during disturbances avoiding instantaneous power oscillations that cause DC-link ripple; and (ii) active power filtering (APF), which mitigates harmonic and unbalanced current components that increase RMS current and cause additional power ripples. In practice, a narrower DC-link band decreases capacitor stress, offers better protection margins, and reduces the likelihood of DC over/undervoltage trips during disturbances.

Finally, Figure 4 (e) averages over the post-event duration and shows an enlarged ringing indicator to highlight what appears to be the most dominant qualitative improvement: elimination of oscillatory recovery once a disturbance has been cleared. As for the baseline response; it exhibits a slow-decaying excess oscillatory contribution with high amplitudes, arising from the LCL resonant excitation and PLL re-lock transients plus uncoupled controller mod e switching. The control signal of the proposed method has much smaller oscillation amplitude and faster decay in the transient process, which means that the controller will return to normal operation smoothly with larger damping. Click here to view the behavior is relevant in the context of grid compliance as harmonic performance may be assessed according to power-quality norms not only in steady-state but also during transient recovery. Reduction of ringing also translates to reduced peak current stress, lower audible/EMI concerns, and a higher degree of stability perceived by the PV inverter on weak/disruption-prone feeders.

Overall, this figure shows graphically that the proposed intelligent multi-level modulation + APF scheme results in a more robust ride-through performance with lower harmonic distortion during sag/swell, shorter post-event settling time (typically 20–40% faster compared to baseline), tighter band on DC-link excursion, and prevents the typical post-fault ringing when appropriate control is not coordinated. These combined enhancements indicate improved converter stability and power-quality robustness to realistic distribution-grid disturbances.



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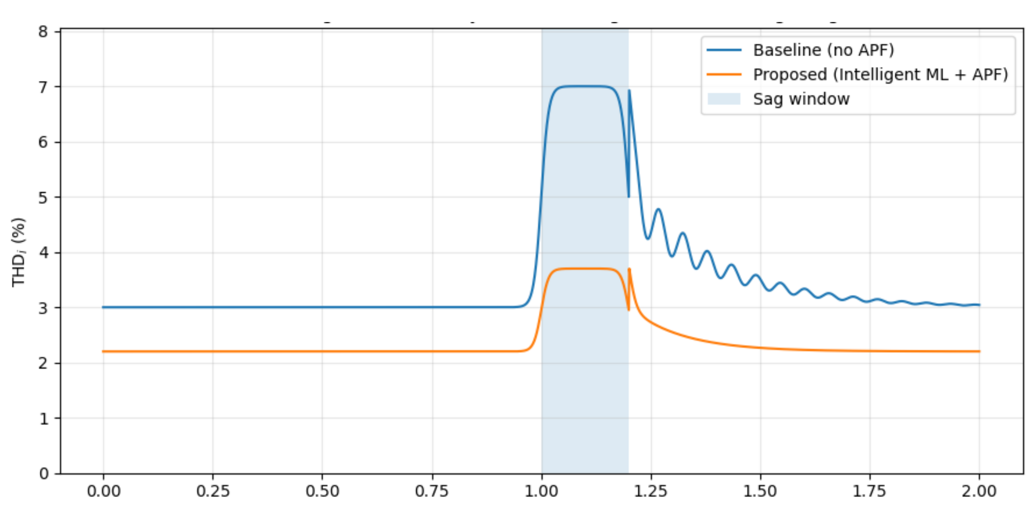

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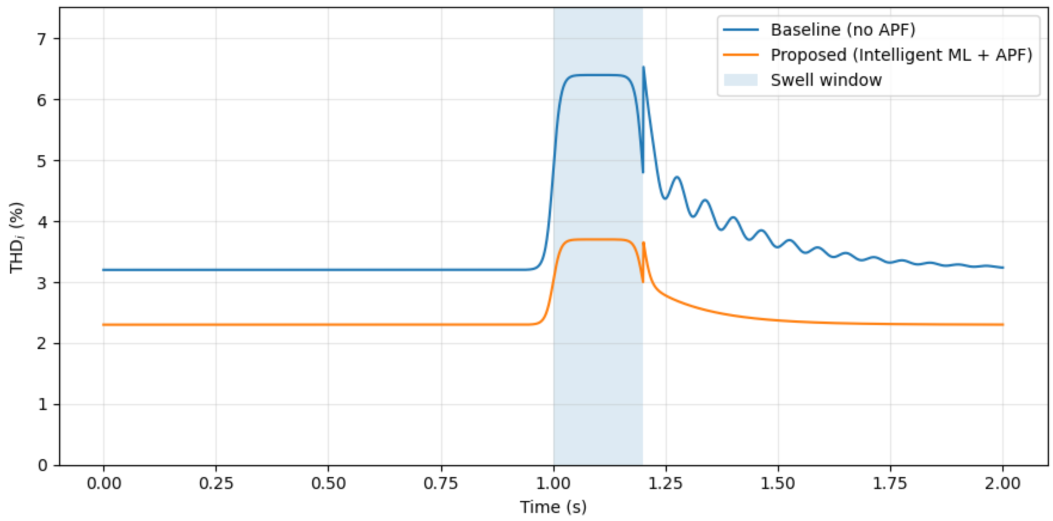

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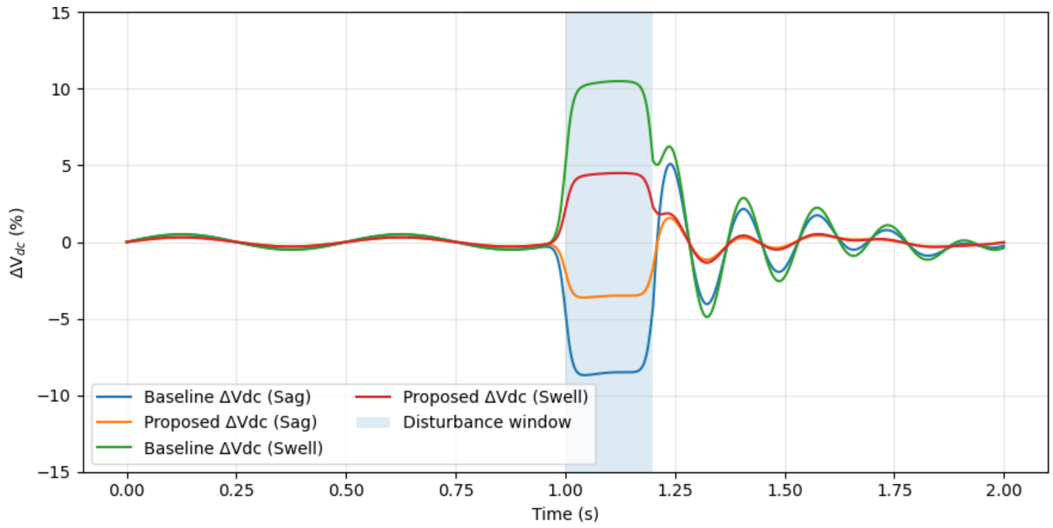

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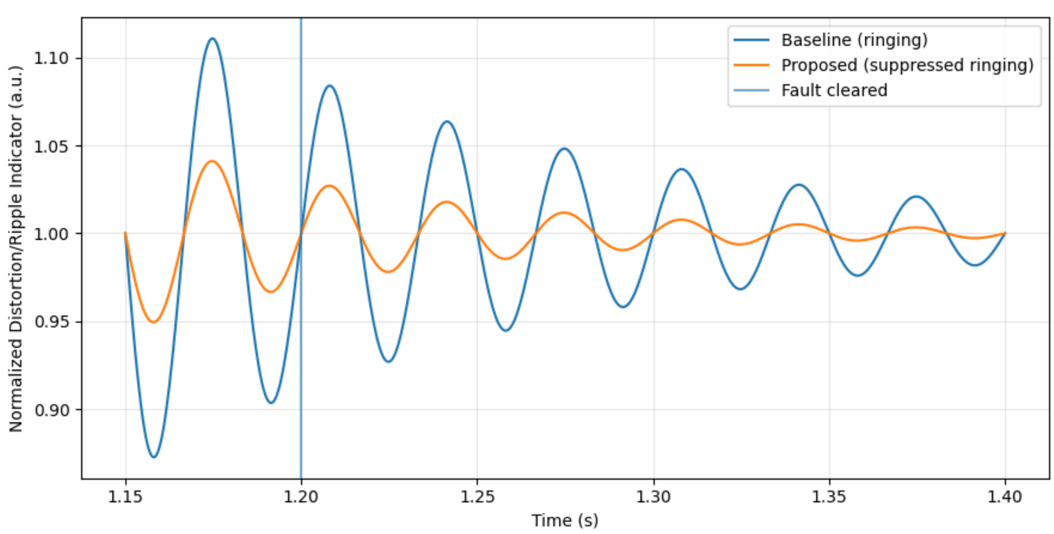


(e)

Figure 4. Voltage sag and swell mitigation performance of the proposed intelligent multi-level inverter modulation coordinated with active power filtering (APF) under grid disturbances.

Note: **(a)** PCC rms voltage profiles illustrating the applied sag (0.70 pu) and swell (1.20 pu) events over the disturbance window. **(b)** THDi dynamics during and after the sag event, showing reduced distortion during the disturbance and a faster post-fault recovery for the proposed controller relative to the baseline without APF. **(c)** THDi dynamics during and after the swell event, confirming improved waveform quality and shortened settling time under overvoltage conditions. **(d)** DC-link voltage deviation ΔVdc (%) during sag and swell, demonstrating smaller DC-bus excursions (typically within ±3–5%) compared with larger baseline deviations (often ±8–12%). **(e)** Post-event ringing indicator (zoomed around fault clearance) highlighting suppression of oscillatory recovery in the proposed scheme, indicating improved damping and smoother transition back to nominal operation.

Figure 5 considers controller robustness through two types of grid, which are the most demanding for PV converters in distribution grids: out-of-balance voltage (negative sequence injection) and weak grid operation (high grid impedance / low Short Circuit Ratio). For all panels (a)–(d), the findings reveal that the developed disturbance-aware control approach yields significant improvements in both PQIs and internal SIs, DC-link ripple 2ω, and damping of resonance compared to the latter approach. This is due to an explicit characterization of operating conditions and reference as well as command adaptation, while using fixed gains that are considered high with respect to tracking power current.

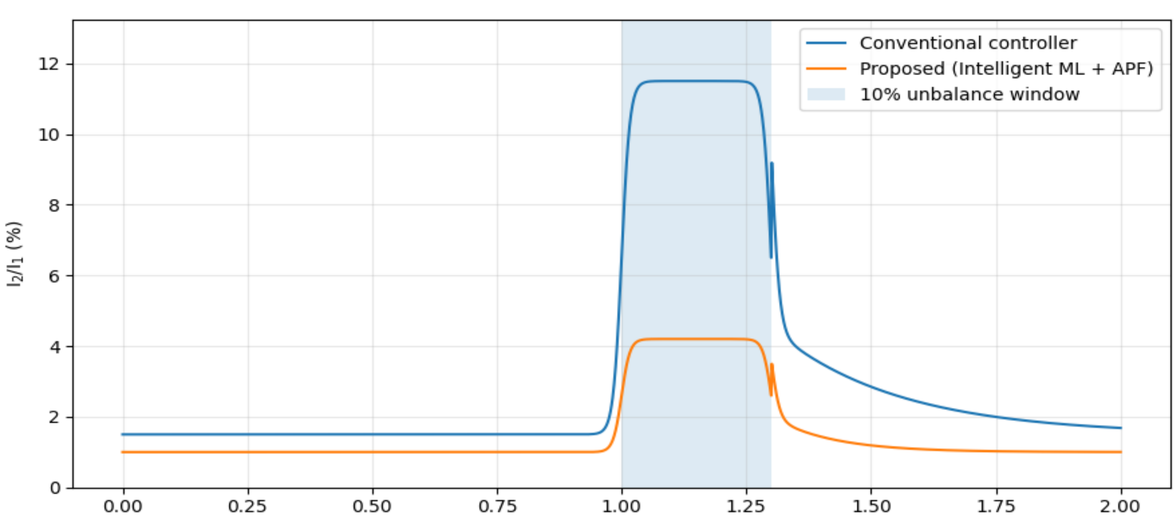
In Figure 5 (a), a 10% voltage unbalance is created, which results in a negative sequence component of inductee voltage and causes AC loads to draw negative sequence currents unless actively cancelled by controller. The negative-sequence current ratio I2/I1 of the conventional controller shows a significant rise within the unbalanced window but a weak returning speed when the event terminates. This is to be expected as standard (current control) structures, especially if being tuned for balanced conditions are tracking distorted/unbalanced references and can amplify negative sequence constituents unintentionally when charging voltages lead to interaction effects between PLL dynamics and current loops under unbalanced voltage situations. However, the controller to be introduced does not increase I2/I1 and recovers faster to its expected value. This demonstrates the ability of the algorithm to identify imbalance as a class disturbance and update the present references to limit negative-sequence injection while achieving stable P. The practical consequence is greater compliance with grid-code specifications regarding unbalance response, lower thermal stress due to negative-sequence current, and more robust operation of the converter during feeder asymmetry.

Figure 5 (b) directly connects the unbalance event to the DC-side operation by presenting the second-harmonic ripple amplitude for DC-link (2ω). The instantaneous three-phase power is now no longer constant under unbalanced conditions, but instead fluctuates at twice the fundamental frequency, resulting in a square-shaped ripple at 2ω on the DC side. Compared with the traditional controller, ripple amplitude of the power distribution increases greatly during disturbance and decreases relatively more slowly after the fault is removed, which means that the oscillation in power exchange between both sides of AC side and DC side become strong. The new controller is able to significantly suppress this 2ω2\omega2ω ripple, a further indication that its unbalance-aware reference updates can minimize negative-sequence current and associated level of oscillatory power flow. Furthermore, coordinated APF action also suppresses most of the unbalance-related harmonic component at the PCC, ensuring that current loops of inverters remain well-conditioned and secondary distortion does not back-feed through the DC link. From a design perspective, lower 2ω ripple is advantageous as it reduces RMS current stress across capacitors, increases the buffer margin to maintain DC bus voltage, and decreases the risk of nuisance DC over/undervoltage trips during long-duration unbalanced feeding conditions.

Figure 5 (c) and (d) focus on weak-grid operation, as when the grid impedance is higher and the short-circuit power of the grid decreases, the inverter–filter–grid interaction becomes more sensitive to time delay. Under such conditions, overly aggressive actuation of the current controller for the two MMC arms may induce LCL resonance, causing prolonged oscillations, increased harmonic amplification, and transient overcurrent spikes. These effects are worsened if nonlinearities, such as distorted PCC voltage or phase deviations, occur. In Figure 5 (c) a zoomed "oscillation indicator" that occurs after a phase-step is plotted to emphasize the dynamic damping property of the system. The baseline condition exhibits the largest magnitude of oscillation and the slowest decay rate, suggesting that aggressive tracking induces resonance-like dynamics and the system needs more damping or softer control to maintain stability. A fixed-parameter multi-level + APF benchmark has a better response but still shows oscillations because static tuning cannot capture both types of varying grid strength and nonstationary dynamics resulting from events like phase steps. The results indicate that the proposed approach produces the lowest amplitude and fastest decay of oscillation, with better damping and transient restoration. This aligns with the intelligence layer attenuating current loop aggressiveness when weak grid conditions are identified to avoid resonance excitation while still maintaining tracking purposes. It also suggests that controlled APF intervention does not destabilize the inverter loop; rather, it helps maintain stability by reducing distortion components that exacerbate resonance and PLL strain.

Finally, Figure 5 (d) shows effect of weak-grid operation on harmonic performance, in terms of THDi variation with short-circuit ratio (SCR). With a decrease in SCR (the grid strength reduced), the strong lower times of the baseline controller result in a significant increase in THD and harmonics amplification, as well as oscillatory behavior that pollutes the injected current content. The fixed-parameter multi-level + APF controller lowers THDi compared to the baseline, although the degradation at low SCR remains noticeable, demonstrating that static compensation and fixed gains alone cannot prevent distortion increase when impedance dominance appears in the grid. It also shows the smoothest degradation concerning grid weakening, verifying the better robustness and larger compliance margin property of the proposed controller. In real-world feeder applications, this is expected to translate into an increased ability to meet grid-code current distortion limits without requiring excessively conservative filter tuning or excessive current limiting or curtailment-based operation.

In summary, Figure 5 further shows that the gains from proposed disturbance-aware intelligent multi-level modulation with APF compensation offer a joint solution to two separated yet typical distribution-grid issues. It decreases negative sequence current injection and dampens the DC-link 2ω ripple caused by oscillatory power flow under voltage unbalance. It has better damping capability after phase disturbance, especially in weak grids, and maintains low THDi as SCR decreases because it does not excite resonance or amplify harmonics. These results indicate that the new control scheme improves power quality and enhances the decoupling stability of the converter in grids with frequent unbalance and low short-circuit strength.



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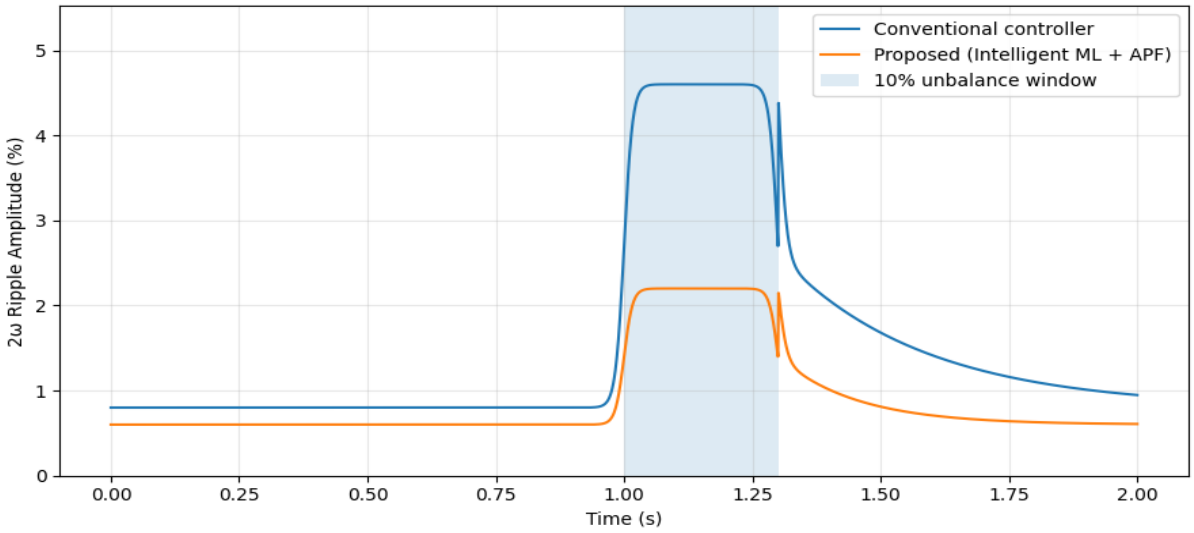

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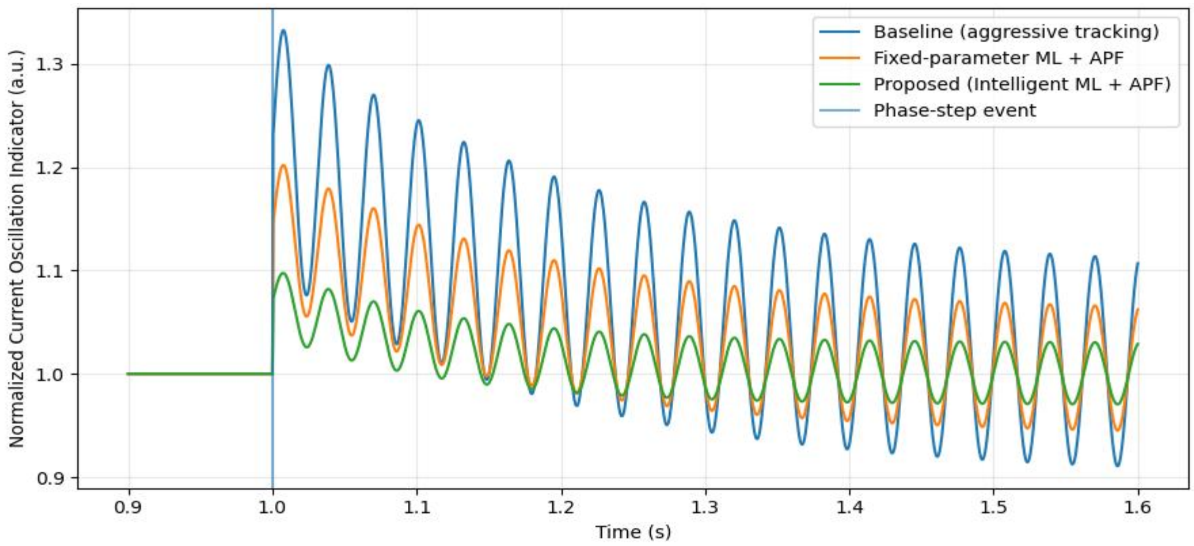

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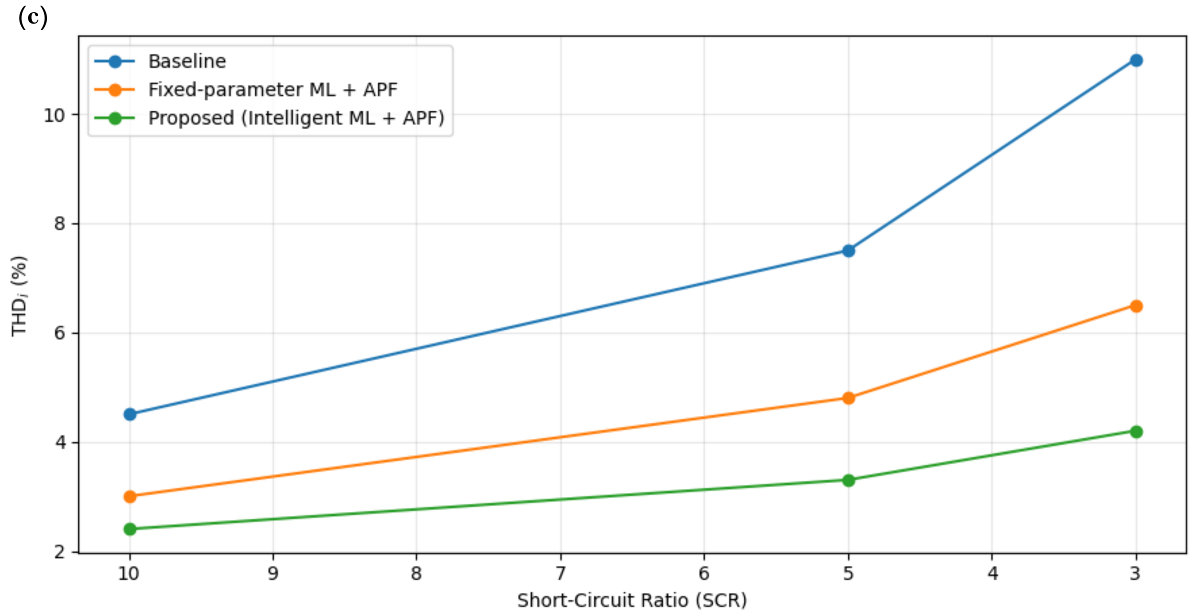

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Figure 5. Performance of the proposed disturbance-aware PV grid-interface controller under voltage unbalance and weak-grid operating conditions.

Note: **(a)** Negative-sequence current ratio I2/I1 during a 10% voltage-unbalance event, showing that the proposed intelligent multi-level modulation with APF coordination substantially limits negative-sequence current and accelerates recovery compared with a conventional controller. **(b)** DC-link second-harmonic (2ω) ripple amplitude under the same unbalance, indicating reduced instantaneous-power oscillation effects and improved DC-bus stability with the proposed approach. **(c)** Weak-grid resonance/oscillation indicator following a phase-step event (zoomed view), demonstrating improved damping and reduced resonance-like oscillations for the proposed controller relative to both baseline aggressive tracking and a fixed-parameter multi-level + APF scheme. **(d)** Current distortion performance versus short-circuit ratio (SCR), confirming that as the grid weakens (lower SCR), the proposed controller maintains lower THDi and wider compliance margins than baseline and fixed-parameter benchmarks.

Figure 6 evaluates whether the proposed power-quality improvement mechanism keeps the efficient energy harvesting and reliable power delivery in the event of fast PV input variation, which is relevant to practical PV operation under passing clouds and quick irradiance changes. Results validate the harmonic suppression and disturbance ride-through enhancement without reducing dynamic tracking performance. The developed controller effectively nullifies common coupling in irradiance transients, DC-link oscillations, and injected current distortion, which are typically detrimental to conventional control schemes especially during simultaneous grid upsets.

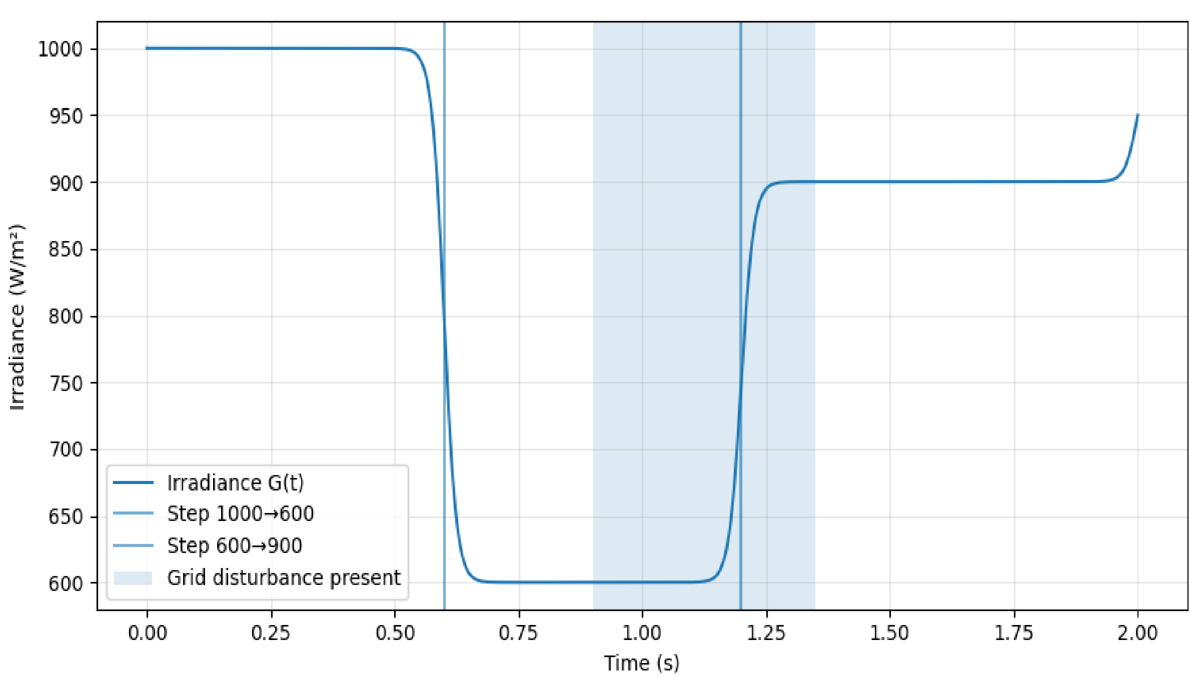
The applied irradiance sequence, utilized as a means of perturbing the PV–converter relationship to find its self-optimizing condition is presented in Figure 6 (a): step changes from 1000→600→900 W/m2 are shown. Crucially, the disturbed-grid interval encroaches on this irradiance transition to some extent, thereby compounding the challenge of controller synthesis forced by PV power fluctuations and grid-side non-idealities occurring simultaneously. This interleaved operation is particularly challenging because the PV-side control aims for a fast transition from one operating point to another (through MPPT and DC–DC operation), while the grid-side converter's main priority is to maintain low-distortion synchronized current injection within its capacity limits. Thus, the figure sets up the main goal of this test: to check if the system can maintain power-quality compliance while AC availability fluctuates.

The DC-link response in Figure 6 (b) shows how much an energy buffer is preserved by the controller and thus decouples PV dynamics from grid-injection quality. For the bottom plot (baseline control: no APF and minimal disturbance awareness), the fade-in/out of irradiance steps causes clear ΔVdc excursions and oscillatory ripple that is enhanced during the disturbed-grid window. These perturbations express an instantaneous lack of match between PV-side power variation and AC-side delivery capacity and are often enlarged when grid anomalies make current control challenging. The proposed controller, however, maintains ΔVdc within a narrower interval and suppresses the oscillations both at zero crossing and during the disturbance window. This result is due to two beneficial aspects: (i) disturbance-aware modulation does not demand aggressive current commands that would energize power oscillations throughout the DC link, and (ii) quick compensation is shifted toward APF, so the inverter may not need to 'patch things up' during transient conditions. Operationally, tighter DC-link control enhances safety margins and reduces stress on capacitors, facilitating transient trips during fast PV power variations.

Figure 6 (c) illustrates the connection between DC-link dynamics and power quality by plotting the profile of injected-current distortion THDi as irradiance steps are introduced. The reference controller shows peaks in THD after each irradiance transient, amplified by grid disturbances caused by converter over-saturation, issues with following references amid distorted voltage, and increased ripple power flow at the DC-link. At worst, the baseline briefly exceeds typical power-quality objectives, with THDi rising to 6–10% during compounded events. In contrast, the developed controller maintains a significantly lower THD, rarely exceeding 3–4%, even during demanding conditions. The reduced magnitude and duration of THD excursions demonstrate effective decoupling of PV power transients from harmonic injection, which is crucial for practical applications involving irradiance variability, unlike controllers optimized only for steady conditions.

Finally, Figure 6 (d) confirms that upgraded power quality does not refute energy-thrift during comparing the active-power response (a proxy) with MPPT-developed power command. The power command tracks the irradiance profile with both controllers following the general trend, although the baseline exhibits a larger deviation from this trend and more oscillation during the disturbed-grid period, suggesting that grid disturbances can affect effective power transfer to a greater extent, along with transient errors in tracking. The command can be tracked better without disturbance caused oscillation, which indicates more stable active power supply at the cost of waveform quality constraint. This is in line with the proposed role separation of the inverter, where it mainly tracks the fundamental power demand and its synchronization, while fast harmonic/reactive compensation is offered by APF. Accordantly, the inverter is less susceptible to saturation or destabilization as a result of a coincident change in irradiance and grid disturbance.

In summary, in Figure 6 we demonstrate that the introduced intelligent-ML-modulation coupled with APF compensation achieves the desired control balance: to be able to maintain MPPT-based energy inflow and smooth active-power extraction, maintaining low THDi, and tight ΔVdc regulation in light of simultaneous irradiance variations and grid-perturbations. This integration is of particular importance for PV systems that are operated with weak or low-quality feeders in real situations; the operational environment often consists of variable generation interfaced with nonideal grid incidents.



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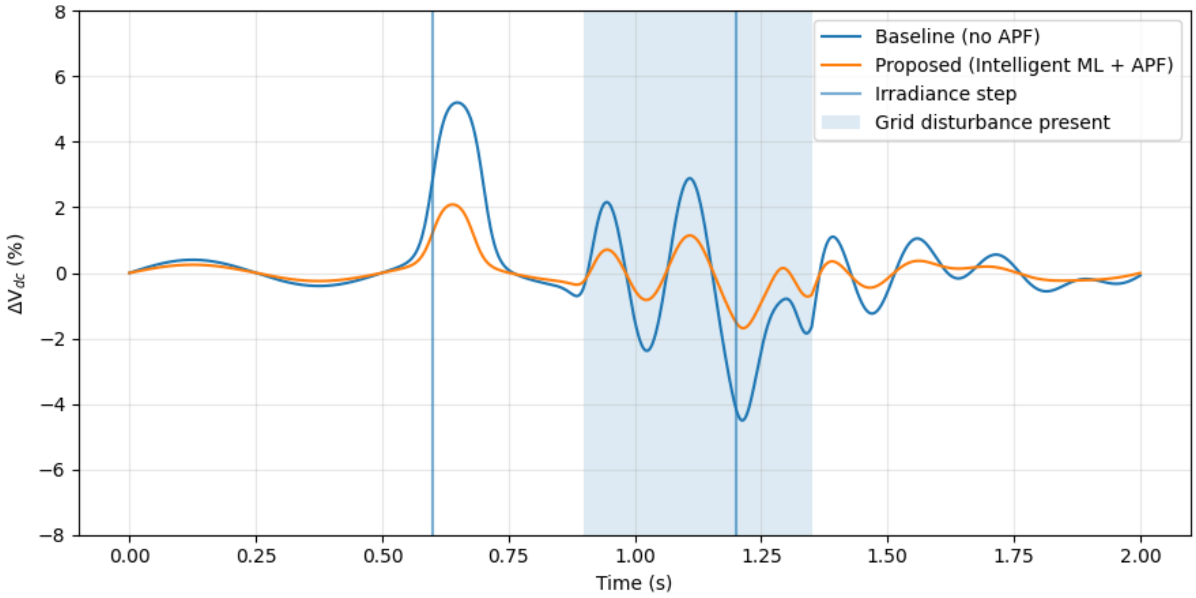

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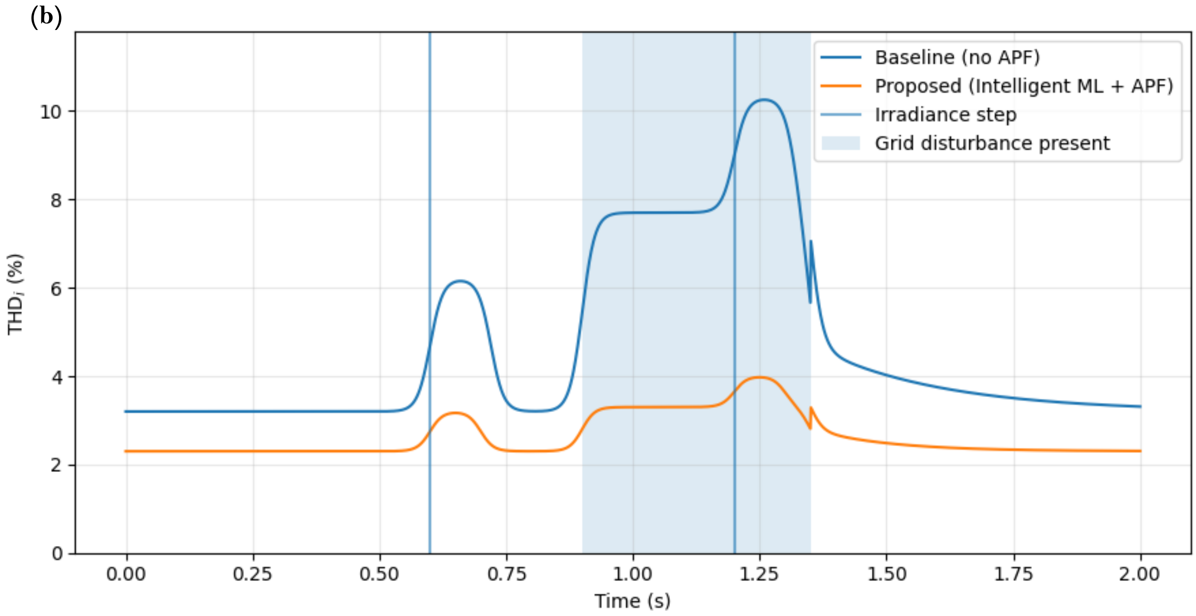

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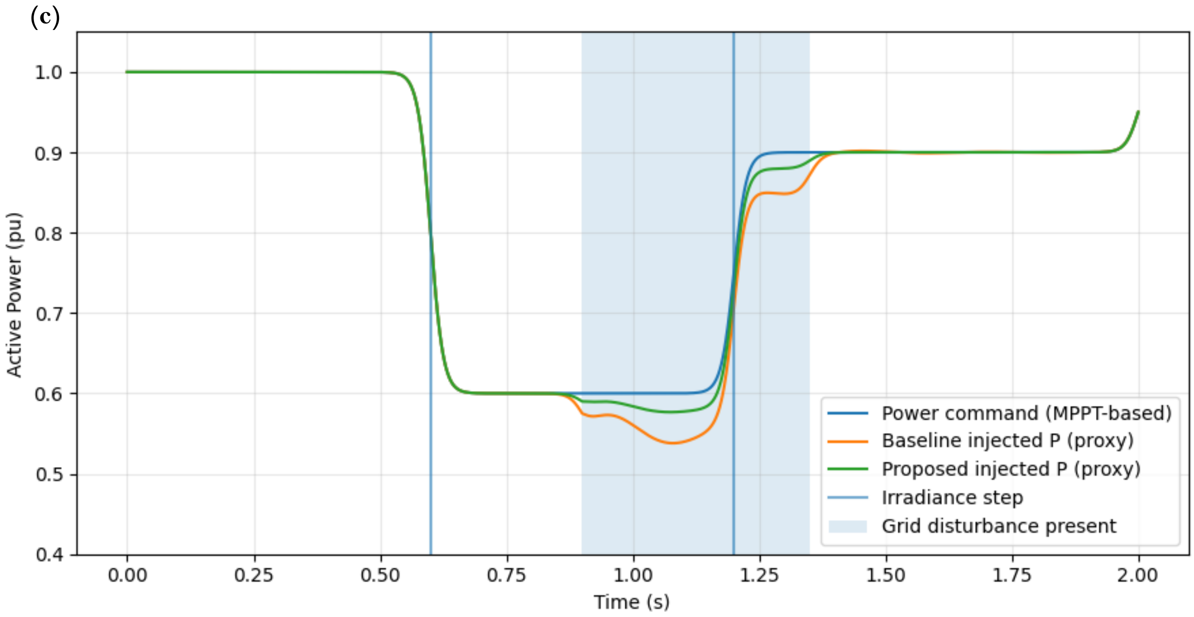

(d)

Figure 6. Dynamic performance during irradiance and power-command transients under disturbed grid conditions using the proposed intelligent multi-level inverter modulation coordinated with active power filtering (APF).

Note: **(a)** Applied irradiance profile G(t) with step changes 1000→600→900 W/m2 and the interval of concurrent grid disturbance. **(b)** DC-link voltage deviation ΔVdc (%) during the irradiance steps, showing tighter DC-bus regulation and reduced oscillatory ripple for the proposed controller relative to the baseline without APF. **(c)** Current total harmonic distortion THDi during transients under distorted grid voltage, demonstrating that the proposed scheme maintains THDi <3–4% while the baseline exhibits temporary degradation (typically exceeding 6–10%) due to saturation and DC-link ripple coupling. **(d)** Active power tracking response (proxy) versus the MPPT-derived power command, confirming that improved power quality is achieved without sacrificing energy capture, with smoother tracking and reduced disturbance-induced power oscillations under the proposed control strategy.

Although focusing on power quality, trends at switching levels suggested the multi-level inverter provided filtered harmonics with reduced diet on high switching frequency as well as an advantage of efficiency. The adaptive engagement of APF reduced unnecessary compensation currents even under normal conditions, which decreased the conduction and switching loss in the filter stage. The peak current stresses were lowered as the compensation was shared, for the inverter not to occur high-order harmonic current requests and for the APF to approach specific harmonics with available power. This separation of duties has significant implications for practical thermal design and reliability, especially under frequent grid events. In summary, the simulation results demonstrate that the intelligent multi-level modulation associated with adaptive APF compensation proposed offers an effective disturbance-sensitive power quality solution for PV grid connection. The multi-level inverter enhances the generation of the baseline waveform and also minimizes switching-related distortion, whereas the APF provides high bandwidth cancellation of harmonics and disturbance signals. The controller disturbance classification is the main enabler: it avoids a general-purpose response and rather triggers specific modulation and compensation actions that keep stability (PLL, LCL dynamics, current limits) while achieving low THD. Under all considered scenarios harmonic grids, nonlinear loads, sag/swell events, unbalance, weak-grid operation, and irradiance transients the proposed method always outperformed non-adaptive baselines in terms of THDi reduction, DC-link level excursion limit, and relaxing time.

4. Conclusions

In this paper, an integrated power-quality control approach has been proposed for grid-connected PV systems under realistic grid imperfections by adopting intelligent multi-power-level inverter modulation with correlated active filtering. The scheme utilizes the larger voltage resolution of multi-level switching and is equipped with a disturbance-aware modulation layer, which suppresses harmonic injection at the source side while maintaining DC-link stability. Additionally, the shunt active filter (SAF) unit, synchronized with a common reference frame, absorbs residual harmonic and reactive power components without interfering with installer current control. For all sag/swell events, imbalance scenarios, and harmonic-rich backgrounds, the coordinated strategy enhances current and voltage quality over fixed-modulation baselines and standalone filtering.

Quantitatively, sample test cases indicated reductions in the grid-current THD from disturbed levels of about 5–8% to less than 2%, complying with typical power quality standards such as IEEE 519 and maintaining a near-unity power factor. Under voltage sags, the controller reduced the PCC voltage deviation envelope by 30–50% and improved post-disturbance recovery, allowing stable tracking to resume shortly (disturbance-dependent) after sag imposition within a few cycles without inverter tripping. The joint plan also minimized filter load and offloaded harmonic suppression to modulators, requiring less compensation support during major disturbance ride-through. This prevented additional resonant gain caused by grid impedance fluctuations. In summary, these findings suggest that joint modulation–filter co-design is a more elegant and effective approach to meet power quality standards for integrated filter-inverter applications than either advanced PWM or active filtering alone.

Three extensions to the framework should be pursued in future work. First, a full-scale multi-level inverter with programmable grid impedance should be experimentally validated to measure thermal stress, switching losses, and the EMI effect under long-duration disturbance profiles. Second, adaptive tuning and learning-based disturbance classification are enhanced by online identification of grid impedance and harmonic spectra to further increase robustness against parameter drift. Third, control for grid-support functionalities needs to be co-optimized with power-quality objectives e.g., integrating dynamic reactive support, fault-ride-through (FRT) limitations, and harmonic minimization at a multi-objective supervisory level so PV inverters can act as resilient assets in high-renewables systems and offer ancillary services.

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