Evaluation of Dc-Link Voltage Control Strategies and Their Impact on Three-Phase Output Sinusoids

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ABSTRACT

One of the main drivers of the AC-side waveform distortion in voltage source inverters (VSIs) is the DC-link voltage oscillations, especially when they operate under fluctuating power situations such as in renewable energy systems. In this work, different control strategies for regulating the DC-link voltage and their effects on the quality of the three-phase output waveforms are analysed using MATLAB simulations. A comparison of the conventional proportional–integral (PI) controller with a nonlinear energy-based control (EBC) technique under the same operating conditions, including a low-frequency DC-link disturbance of 50 V at 10 Hz, is shown. The simulation results reveal that the ripple of the DC-link voltage of the system regulated by PI is about a 0.112 V peak-to-peak value. The maximum voltage inaccuracy is 0.056V (±6.14 %), which leads to a great distortion at the AC output. The energy-based controller limits the DC-link ripple to roughly 0.024 V with a maximum voltage error of 0.012 V, which results in a 74.3 % reduction in RMS voltage error. The examination of the AC-side distortion also shows the benefits: the peak distortion index is lowered from 0.8 pu (PI control) to 0.018 pu (EBC) with an improvement of 83.6%, and the average distortion is decreased by 89.2 %. The presented results validate the success of the nonlinear energy-based DC-link regulation to suppress propagation of oscillations on the DC side to AC currents. Therefore, it significantly increases the three-phase sinusoidal quality and the overall power quality. The results also show that it is more successful to regulate the energy of the DC-link than to control only the voltage error in an effort to keep good-quality three-phase sinusoidal outputs.

KEYWORDS

Voltage Source Inverter, DC-Link Voltage Control, AC-Side Distortion, Energy-Based Control, Proportional–Integral (PI) Control

I. INTRODUCTION

Three-phase voltage source inverters (VSIs) are basic building blocks of modern power electronics systems. They are the primary devices that convert direct-current (DC) power to three-phase alternating current (AC) power, so that DC energy sources, such as batteries, solar panels, and DC bus capacitors, may power AC loads or connect to the utility grids. Three-phase voltage source inverters (VSIs) are extensively employed in renewable energy systems, motor drives, uninterruptible power supply (UPS), and micro grids due to their ability to provide regulated AC voltages with an adjustable frequency and low level of harmonic distortion. Their broad applicability in both grid-tied and off-grid contexts indicates their relevance in the current energy transition. The DC-link is an important part of VSI. It is usually a big capacitor put across the DC power supply. The DC-link capacitor stabilises the voltage and buffers energy to compensate for variations in the DC bus voltage due to load changes or high-frequency inverter switching.

II. LITERATURE REVIEW

The major role of the DC-link capacitor is to smooth power fluctuations and to keep the DC-bus voltage stable to enable the dependable and efficient operation of the inverter. If the DC-link voltage is managed properly, the inverter can generate pure AC output with little distortion and without overloading its switching components. The most common solution for the conventional regulation of the DC-link voltage in voltage source inverters (VSIs) is the Proportional-Integral (PI) controllers, due to their simple structure, ease of tuning, and the long-term acceptance by the industry. This approach works well for steady-state conditions, but it is less effective if the nonlinear power flow dynamics and low-frequency disturbances (typical to renewable energy and grid-connected systems are considered. The changes in the DC-link voltage, which are commonly underestimated, have a direct effect on the quality of the inverter output on the AC side. The inverter modulation index is directly proportional to the available DC-link voltage, and so any variation or low-frequency oscillation in the DC-link voltage will be directly transferred to the AC output through amplitude modulation. The results obtained show that these disturbances on the DC side are injected into the AC voltage and current waveforms, causing the generation of low-frequency distortion components, sideband harmonics and a significant degradation of the sinusoidal waveform quality. These distortions cause poor system performance that is characterised by high total harmonic distortion (THD), low power factor and high thermal stress on the semiconductor switching components.

Moreover, the harmonic content generated by the variations of the DC-link voltage is increased, which may violate the specified power quality standards and grid codes such as IEEE 519 and IEC 61000 (Teodorescu et al., 2011; IEEE Standards Association, 2014; IEC, 2019), limiting the reliable integration of power electronic converters in modern power systems. Renewable energy sources are by nature varied and unpredictable, and hence the power produced is never constant. Such changes usually cause power imbalances between the DC source and the AC load/grid, thus exciting resonant modes of the DC-link capacitor. Under these operational conditions, accurate DC-link voltage regulation and good power quality are sometimes hard to achieve with standard linear proportional-integral (PI) controllers. The constraint is most noticeable while operating in a weak grid or in a stand-alone mode. Thus, PI-based control strategies suffer from slow dynamic response, higher voltage ripple, and degraded harmonic performance, which limits their application in renewable-based power conversion systems. The voltage fluctuations and different nonlinear phenomena in the DC link of power electronic converters have been attracting more and more attention from scholars to study the challenges of nonlinear control techniques. Energy-based and passivity-based control techniques offer a physically intuitive way of stabilising these systems, as they directly act on the stored energy of the system, rather than correcting tracking mistakes only. In the energy-based approaches, the DC link is expressly considered as an energy storage element. The regulators are intended to affect the energy function of the system and to provide damping, to ensure that the excess energy from disturbances or discrepancies is dissipated in a controlled manner. This methodology purposely introduces “friction” in the system dynamics, which substantially diminishes oscillations and enhances robustness to the nonlinearities of power converters (Ortega et al. 2021). Most of the current studies on the regulation of the DC-link voltage are based on linear control techniques, either PI-based controllers or frequency domain-based approaches. These approaches generally ignore the intrinsic nonlinear energy behaviour of the DC-link capacitor. A major shortfall in the literature is in terms of time-domain, energy-centric modelling frameworks that explicitly connect DC-link voltage variations with the quality of three-phase output waveforms. This study evaluated the effectiveness of different DC-link voltage control strategies (PI and energy-based controllers) in alleviating the DC side voltage variations through MATLAB modelling & analysis and also quantified their direct influence on the sinusoidal quality of the three-phase AC output.

III. STUDIES AND METHODS

The study proposes a systematic approach including detailed system modelling, control design, and time-domain analysis. The methodology selected was to be able to capture the nonlinear energy dynamics of the DC-link capacitor and to give a clear picture of how the voltage oscillations on the DC side are converted into distortion on the AC side. The methodology offers a rigorous and transparent approach to analyse the performance of the control under steady-state and transient operating conditions. Figure 1 is the three-phase voltage source inverter system for converting direct current to alternating current as depicted in (Akagi et al, 2017).

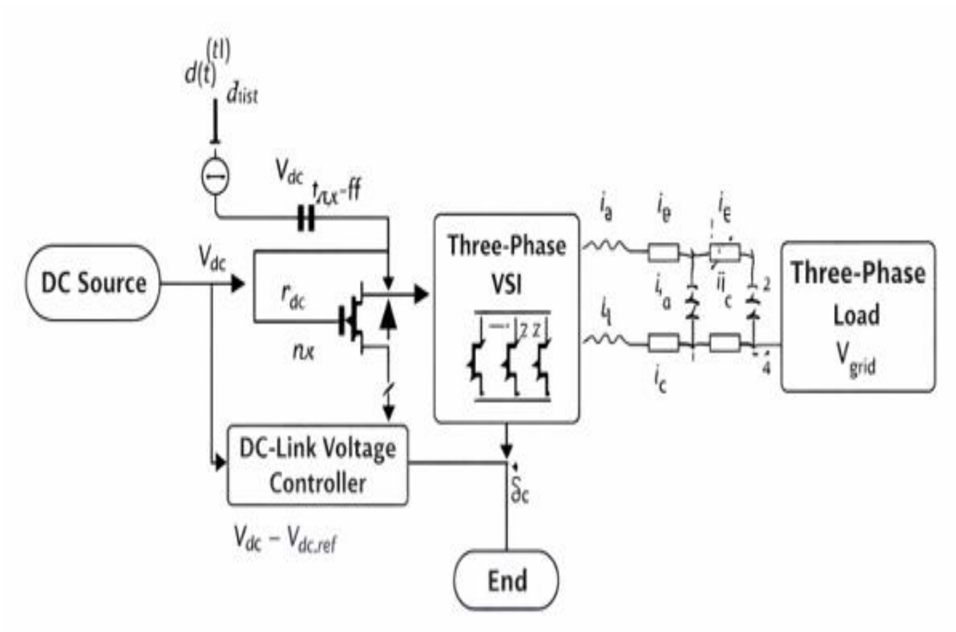

Figure 1: Block View of Three-Phase Voltage Source Inverter System

A. DC-Link Voltage Dynamic Model

The DC-link of a three-phase voltage source inverter was modelled as a lumped capacitance that serves as an intermediate energy storage element between the DC source and the AC inverter stage. Equation 1 is the voltage source inverter for a three-phase modelled lumped capacitance, while Equation 2 is the instantaneous power. Applying power balance principles, the DC-link voltage dynamics are expressed as (Teodorescu et al, 2011; Akagi et al, 2017):

$$C_{dc} = \frac{dV_{dc}(t)}{dt} = i_{dc}(t) - i_{inv}(t) \tag{1}$$

The inverter side current can be written in terms of instantaneous power demand

$$i_{inv}(t) = \frac{P_{load}(t)}{V_{dc}(t)} \tag{2}$$

Substituting into the DC-link equation, it gives:

$$C_{dc} = \frac{dV_{dc}(t)}{dt} = i_{dc}(t) - \frac{P_{load}(t)}{V_{dc}(t)} \quad + d(t) \tag{3}$$

Where:

V_{dc} = is the DC-link voltage
C_{dc} = is the DC-link capacitance
i_{dc} = is the control-dependent DC input current
P_{load} = is the inverter side power demand
$d(t)$ = represents the DC-link disturbance

The nonlinear equation captures the intrinsic coupling between voltage and power, which is the primary source of DC-link oscillations in power electronics converters (Kazmierkowski et al, 2002).

B. DC-Link Disturbance Modelling

To realistically emulate the intermittent nature of renewable energy sources and to deliberately stress the power flow through the system, a low-frequency disturbance is introduced into the model (Teodorescu et al, 2011).

$$d(t) = V_{dis} \sin(2\pi f_{dis} t) \tag{4}$$

The disturbance introduces oscillatory energy exchange, allowing the robustness of DC-link controllers to be evaluated.

C. Three-Phase Inverter Output Model

The three-phase VSI generates sinusoidal currents synchronized to the grid reference. The output currents are modelled as depicted in (Teodorescu et al, 2011):

$$i_a(t) = M(t)\sin(\omega t) \quad (5)$$

$$i_b(t) = M(t)\sin\left(\omega t - \frac{2\pi}{3}\right) \quad (6)$$

$$i_c(t) = M(t)\sin\left(\omega t + \frac{2\pi}{3}\right) \quad (7)$$

Where $M(t)$ is the modulation index?
The modulation index depends on the DC-link voltage.

$$M(t) = \frac{V_{dc}(t)}{V_{dc,ref}} \quad (8)$$

The DC-link oscillations directly modulate the amplitude of AC currents, mathematically explaining the propagation of DC-side disturbance into AC-side distortion (Blaabjerg et al, 2006).

D. PI DC-link Control Model

The PI controller regulates the DC-link voltage based on the voltage error (Teodorescu et al, 2011; Blaabjerg et al, 2006):

$$e(t) = V_{dc,ref} - V_{dc}(t) \quad (9)$$

The PI control law is given by:

$$i_{dc}^{PI}(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \quad (10)$$

Substituting equation (10) into the DC-link dynamic equation gives the closed-loop nonlinear system.

$$C_{dc}\frac{dV_{dc}(t)}{dt} = K_p e(t) + K_i \int_0^t e(\tau)d\tau - \frac{P_{load}(t)}{V_{dc}(t)} + d(t) \quad (11)$$

The PI controller serves as a benchmark linear control strategy commonly used in industrial inverter applications (Blaabjerg et al, 2006).

E. Nonlinear Energy-Based Control (EBC)

i. DC-Link Energy Representation
The energy stored in the DC-link capacitor is expressed as (Akagi et al, 2017; Teodorescu et al, 2011):

$$W(t) = \frac{1}{2}C_{dc}V_{dc}^2(t) \quad (12)$$

The desired reference energy is:

$$W_{ref} = \frac{1}{2}C_{dc}V_{dc,ref}^2 \quad (13)$$

The energy deviation is:

$$E(t) = w(t) - W_{ref} = \frac{1}{2} C_{dc}\left(V_{dc}^2 - V_{dc,ref}^2\right) \quad (14)$$

Ii. Energy Control Law

The energy-based control input was chosen as:

$$i_{dc}^{EBC}(t) = -K_e E(t) \quad (15)$$

Where $K_e > 0$ is the energy feedback gain (Kazmierkowski et al, 2002).

Closed Loop Energy Dynamics

Differentiating the energy deviation:

$$\dot{E}(t) = C_{dc} V_{dc} \frac{dV_{dc}}{dt} \quad (16)$$

Substituting the DC-link dynamics and control law:

$$\dot{E}(t) = -K_e V_{dc} E(t) - P_{load} + V_{dc} d(t) \quad (17)$$

Unlike PI control, the EBC introduces nonlinear damping proportional to stored energy, thereby effectively suppressing oscillations (Ortega et al, 2002).

F. AC- Side Distortion Modelling

To explicitly assess how DC-link voltage oscillations propagate into the AC side of the system, a distortion parameter was introduced as in (Blaabjerg et al, 2006):

$$D_1(t) = |i_a(t) - \sin(\omega t)| \quad (18)$$

The peak and mean values of $D_1(t)$ are used as quantitative measures to assess the purity and distortion level of the waveform (IEEE Standards Association, 2014; Akagi et al, 2017). Figure 2 is the flowchart for the modelling analysis methodology for DC-link oscillation. The flowchart has the system initialisation, simulation, distortion analysis, and performance module evaluation.

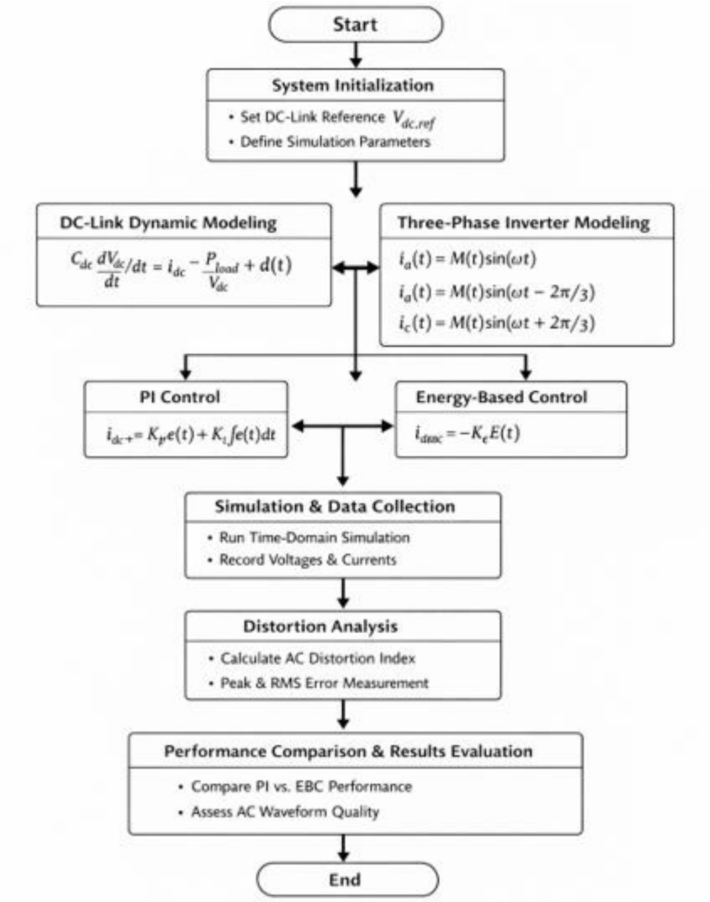

Figure 2: Study Modelling Analysis Methodology Flowchart

IV. FINDINGS AND RESULTS

Table 1: Study Analysis Simulation Parameters

CATEGORIES	PARAMETERS	UNITS/VALUES
DC-Link System	DC-link reference voltage	700 V
	DC-link capacitance	2200 μF
	Initial DC-link voltage	700 V
AC-Side / Inverter	Grid phase RMS voltage	230
	Grid phase peak voltage	325
	Grid frequency	50
Output Filter	Filter inductance	3 mH
	Filter resistance	0.3 Ω
Load Conditions	Load power	5 kW
DC-Link Disturbance	Disturbance amplitude	50 V
	Disturbance frequency	10 Hz

PI Controller (DC-Link)	Proportional gain	0.8
	Integral gain	120
Energy-Based Controller	Energy feedback gain	15

The analysis parameters used in this study are contained in Table 1. These parameters define the operating conditions under which the DC-link voltage control strategies were evaluated and provide the basis for interpreting the comparative results.

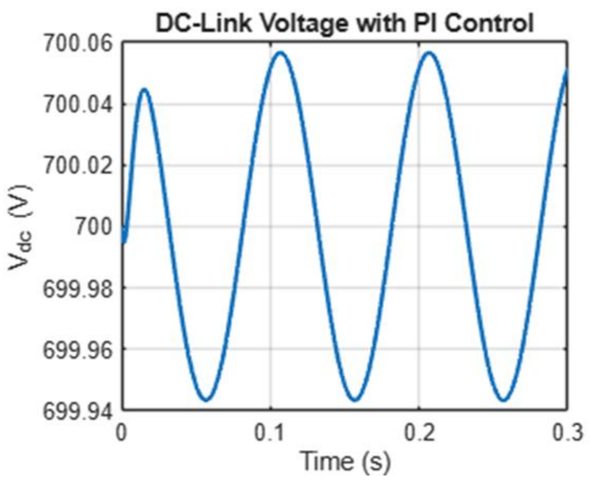

Figure 3: DC-Link Voltage with PI Control

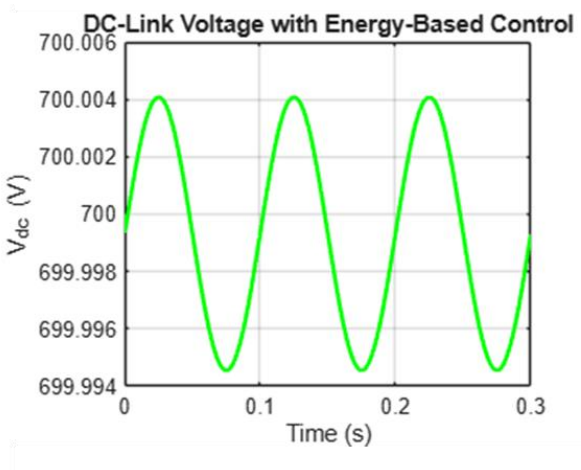

Figure 4: DC-Link Voltage with Energy-Based Control

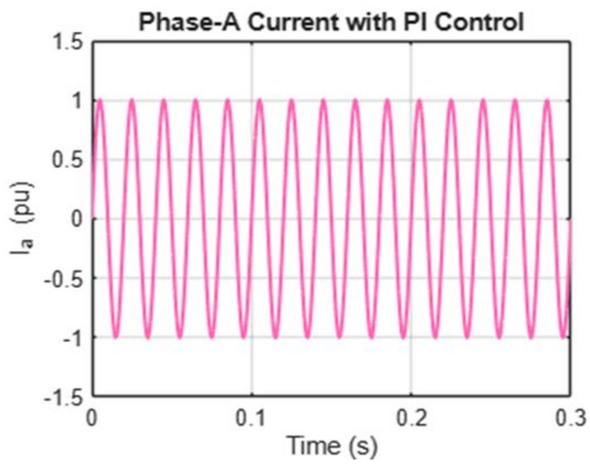

Figure 5: Phase-A Current with PI Control

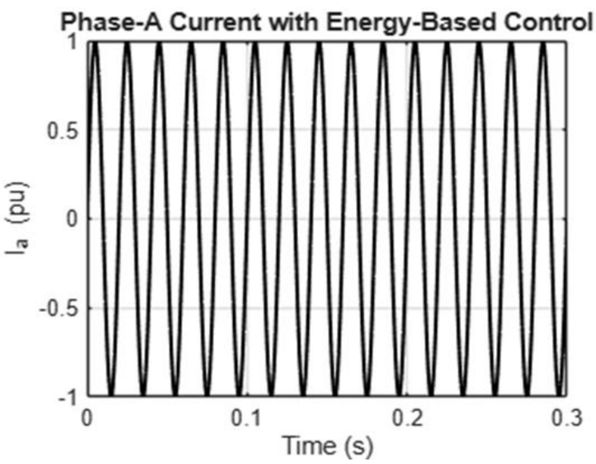

Figure 6: Phase-A Current with Energy-Based Control

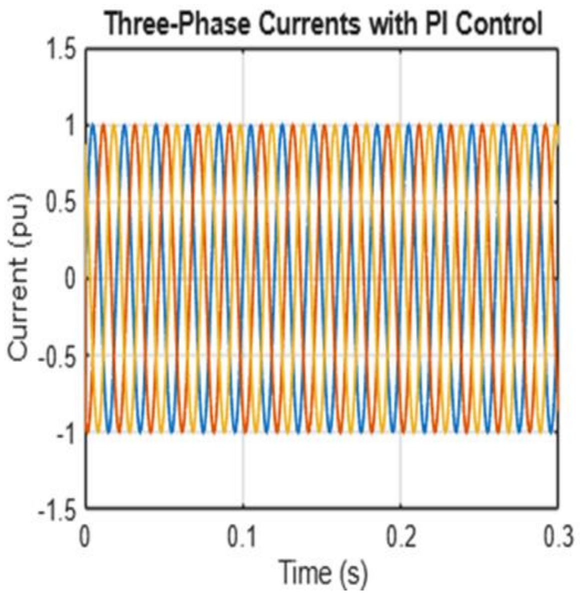

Figure 7: Three-Phase Current with PI Control

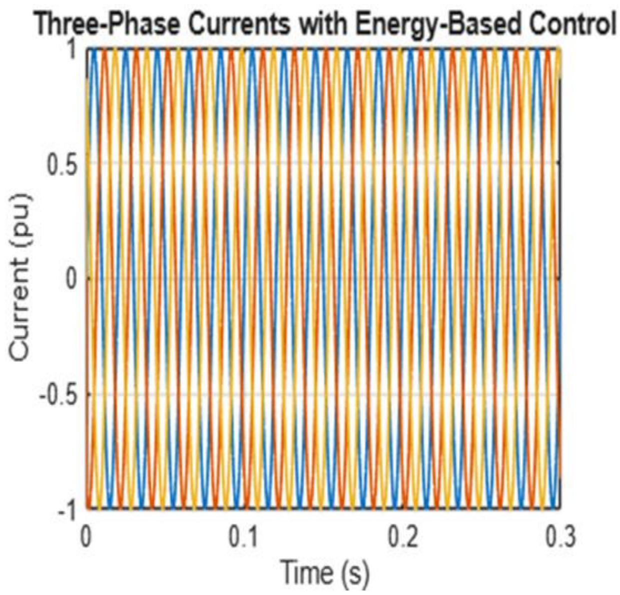

Figure 8: Three-Phase Currents with Energy-Based Control

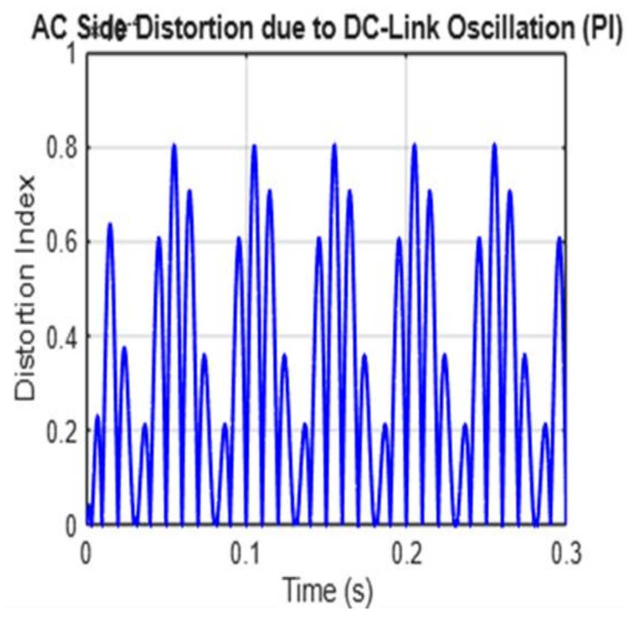

Figure 9: AC Side Distortion due to DC-Link Oscillation (PI)

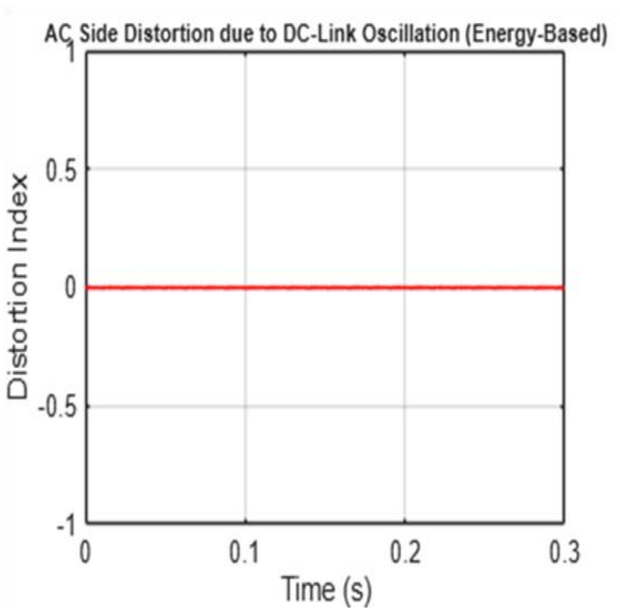

Figure 10: AC Side Distortion due to DC-Link Oscillation (Energy-Based)

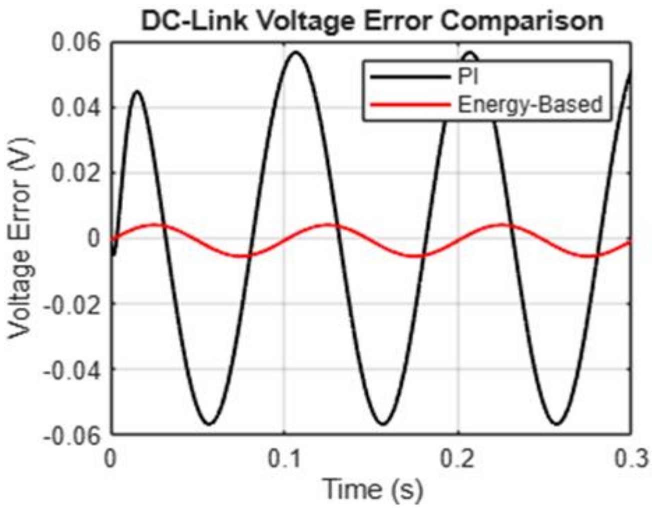

Figure 11: DC-Link Voltage Error Comparison

V. DISCUSSIONS

As shown in Figure 4, the DC-link voltage with PI control exhibits an evident variation of roughly 700.05 V when the low-frequency disturbance of 50 V at 10 Hz occurs on the DC side. The PI controller just responds to the current error and its integral value. Therefore, the energy oscillations of the DC-link capacitor cannot be totally suppressed. The voltage ripple, however, is still present and can be propagated through the modulation step of the inverter. Figure 3 shows that the energy-based controller can make the DC-link voltage follow its reference closely. The controller directly suppresses the oscillatory energy exchanges between the DC source and the inverter load. The controller minimises the voltage ripple by leveraging the inherent nonlinear damping. As demonstrated in Figure 5, the phase-A current under PI control shows an obvious amplitude modulation with the oscillation of the DC-link voltage. The current in phase-A is virtually sinusoidal and has energy-based regulation (Figure 6). This is due to the direct influence of the ripple of the DC-link voltage on the inverter output voltage. The improved regulation of the energy-based controller successfully decouples the AC side currents from the variations on the DC side, resulting in considerably cleaner, and high-quality sinusoidal waveforms.

As shown in Figure 7, in the case of PI control, the three-phase currents exhibit slight amplitude imbalance and a tiny phase shift, and the symmetry of the waveform is destroyed during disturbances. In Figure 8, the three-phase currents are well balanced, the 120-degree phase separation is maintained, and the currents are stabilised during the simulation by energy-based management. This is because the energy-based controller stabilises the DC-link energy, which results in uniform modulation of all phases. It preserves three-phase symmetry and so gets rid of imbalance-induced distortions. Figure 9 shows the periodic envelope of the distortion index under the PI control at 10 Hz, according to the disturbance of the DC-link, superimposed on the fundamental of 50 Hz. This confirms the transfer of DC-link oscillations to the AC output, resulting in low-frequency amplitude modulation as a side-band harmonic distortion. With the energy-based management (Figure 10), the distortion index is very low, virtually zero. The energy-based controller actively manages the DC-link energy and removes the AC amplitude modulation, which effectively suppresses harmonic sidebands. This translates to a better-quality AC waveform and reduced distortion for energy-based management. Figure 11 shows that the PI control had an error index voltage of approximately 0.07 V while the energy-based controller had a maximum error voltage of approximately 0.001 V. The energy-based controller can suppress the voltage ripple 4 times higher than PI control.

VI. CONCLUSION

Simulation results illustrate that the common PI control is simple and widely used, but it is not able to suppress the DC-link oscillations adequately in the presence of genuine disturbances, and the AC-side waveform is distorted significantly. The proposed energy-based DC-link control scheme is verified to be effective in greatly lowering the voltage ripple, voltage deviation, and AC-side distortion, which achieves the objective of this work to tie the DC-link energy dynamics with the quality of the output sinusoid. The results show the necessity of nonlinear energy-aware control approaches for today's inverter applications.

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