

Article

Non-Invasive Supply Voltage Unbalance Detection and Monitoring in AC/DC/AC Converters Using DC-Link Current Analysis

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Abstract

This paper presents a single-sensor solution for the detection and monitoring of power supply voltage unbalances in AC/DC/AC converters. By analyzing the DC-link input current, it is demonstrated that characteristic current pulse deformations directly indicate the presence and severity of grid voltage imbalances. Based on these pulse profile variations, a novel diagnostic metric termed the Current Ripple Voltage Unbalance Factor (CRVUF) is derived. The proposed methodology was comprehensively evaluated and validated through both simulation studies and experimental testing. The presented approach offers a computationally efficient, non-invasive alternative to conventional monitoring systems, effectively reducing the number of required voltage sensors from three to a single current sensor.

Keywords: voltage unbalance; voltage imbalance; power quality

1. Introduction

Voltage unbalance (also known as imbalance) occurs when the Root Mean Square (RMS) of the power supply phases are uneven. It may occur due to the asymmetrical distribution of single-phase loads across phases and even of two-phase loads such as high-speed rail power supply systems [1]. Moreover, fast charging of electric vehicles also contributes to an increased imbalance of grid voltage [2]. The disturbances in the grid that lead to this voltage unbalance could be the result of cyber-physical attacks [3]. This imbalance can be the source of multiple power-quality-related issues.

As can be seen in Figure 1, unbalance leads to higher DC-link voltage ripples and a lower dominant frequency of them. These changes influence the power fed to the inverter in AC/DC/AC systems. This phenomenon is connected with switching rectifier operation mode from continuous three-phase to discontinuous single-phase mode [4].

The continuous rectifier operation (balanced power supply) DC-link voltage U_{DC} value can be described as

$$U_{DC} = \begin{cases} U_{AB} \cos(\theta) & \alpha_{AB} \leq \theta < \alpha_{BC} \\ U_{BC} \cos(\theta - \frac{\pi}{3}) & \alpha_{BC} \leq \theta < \alpha_{CA} \\ U_{CA} \cos(\theta - \frac{2\pi}{3}) & \alpha_{CA} \leq \theta < (\alpha_{AB} + \pi) \end{cases} \quad (1)$$

where U_{AB} , U_{BC} , U_{CA} are the maximum phase-to-phase voltage values, θ is the angle and the α values are the starting conduction angles of the corresponding input voltages.



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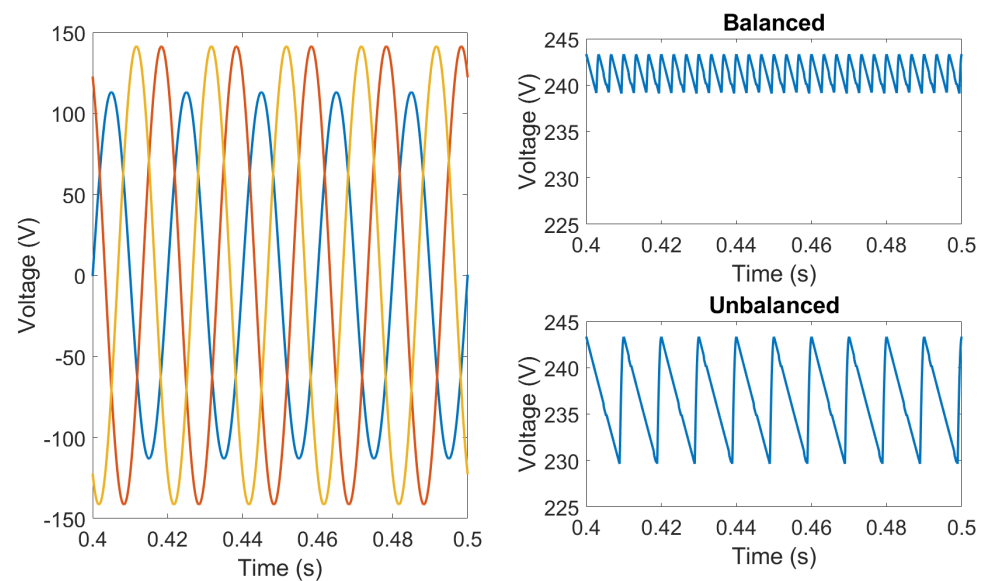


Figure 1. Unbalanced power supply voltage with DC-link voltage comparison between balanced and imbalanced conditions.

In case of discontinuous single-phase operation, U_{DC} is partially dependent on the highest phase-to-phase voltage (U_{max}) and transient discharge of the rectifier load:

$$U_{DC} = \begin{cases} U_{max} \cos(\theta) & \alpha_{max} \leq \theta < (\frac{\pi}{2} - \delta) \\ \text{Load transient} & (\frac{\pi}{2} - \delta) \leq \theta < (\alpha_{max} + \pi) \end{cases} \quad (2)$$

the δ being the phase shift of the load impedance.

The DC-link input current I_1 is also affected by such unbalance as it is directly dependent on DC-link voltage U_{dc} as well as circuit impedance Z at the time of conducting:

$$I_1 = U_{DC} Z \quad (3)$$

Voltage imbalance may cause increased vibrations and torque inconsistencies in electrical drives [5]. Uneven power supply RMS leads to lower transformer efficiency [6] and excessive heating of electrical motors [7].

In order to detect and monitor the AC power supply unbalance of power converters, various solutions have been proposed. One of those is the utilization of the second-order generalized integrator to calculate the positive and negative components of the three-phase voltage [8]. The other solution is to use cross-coherence estimators that calculate linearity between each phase's voltage signals to detect and measure imbalance [9]. The voltage imbalance can also be monitored using machine learning algorithms that help estimate negative components [10]. Enhanced unbalance monitoring can be performed by utilizing additional information on the temperature and efficiency of an electrical motor connected to the converter [11]. Voltage imbalance can be detected not only in voltage but also in current readings, as is presented in [12] where the current space vector is used for wavelet packet decomposition. The solutions presented in [8–12] require the measurement of voltages in each phase, which means the usage of three independent sensors or even six if current data are needed. On the other hand, DC-link voltage can be utilized as an unbalance indicator based on its Fast Fourier Transform (FFT)- [13] or maximum-pulse-voltage-based Voltage Unbalance Factor (VUF) [14]. Moreover, the harmonics of DC-link ripples can be extracted for imbalance monitoring using wavelet transform or bispectral analysis [15].

The proposed method uses a singular DC-link input signal I_1 of an AC/DC/AC converter, which is measured by a single sensor instead of three. Moreover, current

sensors are in most cases more economically reasonable than voltage sensors. The solution presented in this paper is less complex than FFT approach. In Table 1, a comparison of the proposed method with other ones mentioned is provided.

Table 1. Method comparison.

Method	Unbalance Indicator	Number of Sensors	Complexity
[8]	Input-phase voltages	3	Requires complex value additions and multiplications
[9]	Input-phase voltages and currents	6	Cross-coherence between each phase's voltage and current needs to be calculated
[10]	Input-phase voltages and currents	6	After extraction of harmonics, symmetrical components must be calculated
[11]	Temperature and efficiency	5	Temperature obtained based on thermal model with phase currents as inputs; afterwards, unbalance factor is a weighted output of temperature and efficiency
[12]	Input-phase currents	3	After obtaining current space vector, wavelet package decomposition is performed on it
[13]	DC-link voltage	1	FFT performed in order to obtain magnitude harmonics that indicate unbalance
[14]	DC-link voltage	1	Three local DC-link maximum values obtained in order to calculate VUF in a similar fashion to three-phase solutions
[15]	DC-link voltage	1	Wavelet transform or bispectral analysis used in order to obtain harmonics' magnitudes
Presented solution	DC-link input current	1	Current segment compared to model and difference between them integrated

2. Proposed Method

The approach presented in this article focuses on voltage source unbalance diagnostics in the AC/DC/AC converter (Figure 2). The converter is fed from a three-phase voltage source where each phase voltage U_{AC} of RMS V , phase shift φ and frequency ω can be described in the time t domain as

$$U_{AC} = V\sqrt{2}\sin(\omega t + \varphi). \quad (4)$$

The AC voltage is transferred to the six-pulse uncontrolled rectifier, where it becomes the DC signal U_{DC} . Ripples of this voltage are damped with the help of a DC-link capacitor. Two parameters that sufficiently describe the capacitor in the ripple frequency range are capacitance C and Equivalent Series Resistance (ESR). Knowing the capacitor current I_C , the rectified voltage can be presented as

$$U_{DC} = (ESR)i_C(t) + \frac{1}{C} \int i_C dt. \quad (5)$$

U_{DC} is fed to the inverter, that is controlled with a scalar algorithm. The load of the inverter is a resistance and inductance connection in a Y configuration. Such a load represents the stator winding of an electrical motor regardless of rotor type.

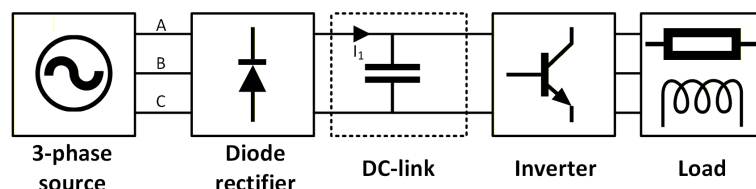


Figure 2. AC/DC/AC converter diagram.

The monitoring of the imbalance condition is performed by obtaining the Current Ripple Voltage Unbalance Factor (CRVUF), which is based on the current I_1 . This current consists of pulses from each input phase of a rectifier, meaning that is affected by the voltage unbalance.

2.1. DC-Link Current Ripple Change

When the voltage is unbalanced, the ripples of the DC-link current I_1 produce uneven pulses (Figure 3). As the imbalance increases, the difference between balanced and imbalanced current ripple becomes more pronounced. Based on that observation, it is possible to monitor and detect a power supply voltage unbalance.

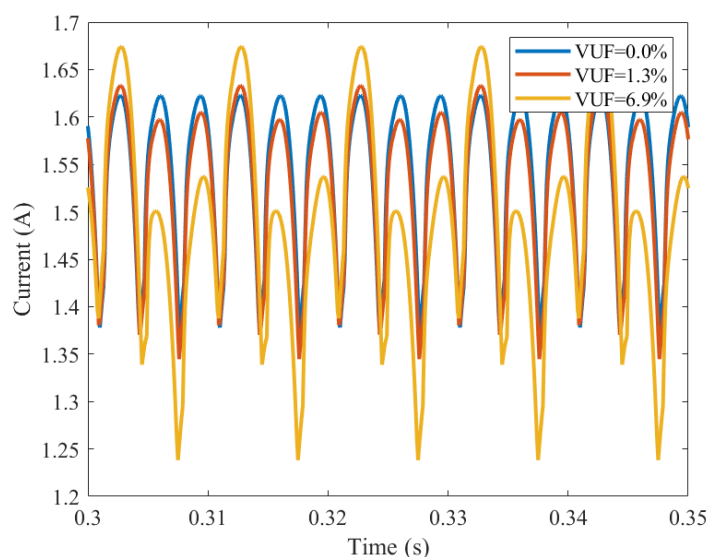


Figure 3. I_1 waveforms at different VUF levels.

The VUF (6) presented in the paper is based on ANSI C84.1-2016. VUF is described as the maximum deviation V_{maxd} of a phase voltage (V_a, V_b or V_c) from the average voltage V_{avg} to the average voltage.

$$VUF = \frac{V_{maxd}}{V_{avg}} 100\% \quad (6)$$

2.2. Current Ripple Voltage Unbalance Factor Calculation

The main idea behind the proposed CRVUF method is to generate ideal ripple based on the three sine functions that overlap and compare it to the measured I_1 after converting the signal by scaling it to a reference per unit and removing the offset (Figure 4). The reference function is the maximum of three absolute values of sine waves that have a phase shift of $\frac{2\pi}{3}$. That function f is described as

$$f(\omega t) = \max[|\sin(\omega t)|, |\sin(\omega t + \frac{2\pi}{3})|, |\sin(\omega t - \frac{2\pi}{3})|]. \quad (7)$$

As can be seen in Figure 3, the unbalanced current pulses repeat periodically in groups of three—acquiring that many pulses is enough to obtain complete information

on voltage imbalance. The comparison is carried out by obtaining the absolute difference ΔI between the generated f and measured I_1 sets of three pulses. Afterwards, CRVUF is represented by the trapezoidal integer ΔI . The integer of ΔI provides the information on the size of the area between f and I_1 which is the intuitive way of assessing the discrepancies between two waveforms.

$$CRVUF = \int \Delta I \quad (8)$$

This solution allows monitoring of voltage source unbalance using only three pulses of I_1 and a single current sensor.

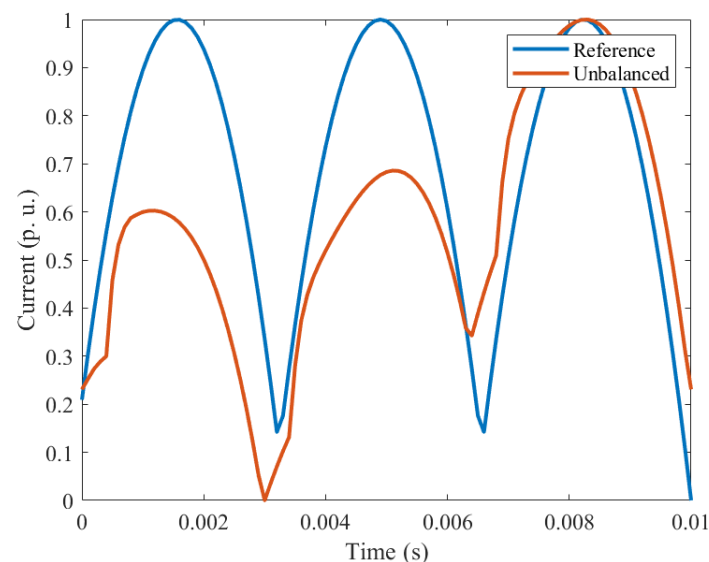


Figure 4. Comparison of reference and simulated unbalance current.

The VUF and CRVUF are both based on the supply voltage unbalance where unequal phase RMS lead to uneven voltage ripples (1) or in extreme cases to single-phase rectifier operation (2). That phenomenon makes it possible to use U_{DC} as the unbalance indicator as proven in [13–15]. Based on the relationship between U_{DC} and I_1 (3), the CRVUF value can be utilized in voltage unbalance assessment.

3. Simulation Validation

The simulations were performed in the MATLAB 2023b/Simulink 23.2 environment. The models were calculated using the backwards Euler method with a computation step of 1×10^{-7} . However, the sampling period of the signals was 1×10^{-4} in order to emulate real signal acquisition systems.

3.1. Model and Approach

The model topology is the same as that presented in Figure 2. The load of the model is the three-phase Y connection of resistance and inductance in each leg. The key parameters of the model are presented in Table 2.

Table 2. Model key parameters—balanced condition.

Parameter	Value
R per phase (Ω)	50
L per phase (mH)	2.5
Voltage per phase (V)	100

The approach to simulation validation consisted of multiple calculation runs of the model in different configurations of the power supply phase voltage (V_a , V_b , V_c) presented in Table 3. After obtaining I_1 records, the procedure described in Section 2.2 was conducted. As a validation, CRVUF was compared with VUF based on phase voltage measurements (6).

Table 3. Voltage unbalance cases for CRVUF method tests.

Case	V_a (V)	V_b (V)	V_c (V)
1	100	100	100
2	99	100	100
3	98	100	100
4	95	100	100
5	90	100	100
6	80	100	100
7	99	99	100
8	98	98	100
9	95	95	100
10	90	90	100
11	80	80	100

3.2. Validation Results

As can be seen in Figure 5, both VUF (6) and CRVUF (8) have a similar nature of factor change. This observation shows that CRVUF is a valid indicator of unbalanced voltage in the power supply. The offset between curves is present because of the differences between I_1 and the ideal ripple shape even under balanced conditions. It can be seen that CRVUF is more prone to changes under two-phase imbalance than VUF. The observed VUF reaches values above 10%, which is above the recommended detection point (2%) and the accepted unbalance value (5%) according to IEEE recommendations [16]. Those changes confirm the correct choice of the case parameters in Table 3.

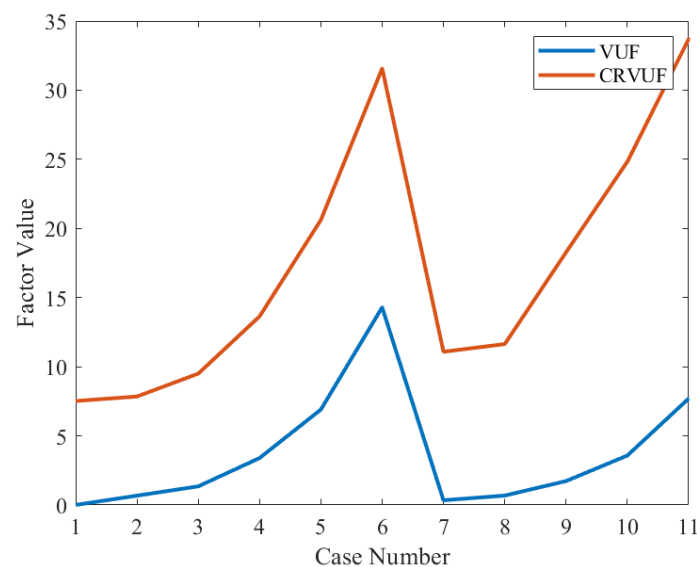


Figure 5. Comparison between VUF and CRVUF in relation to unbalance case.

3.3. Parameter Change Analysis

Voltage imbalance can also be caused by a phase shift change, influencing the I_1 waveform. Figure 6 shows that phase shift change can also be detected using CRVUF as it increases due to the phase unbalance.

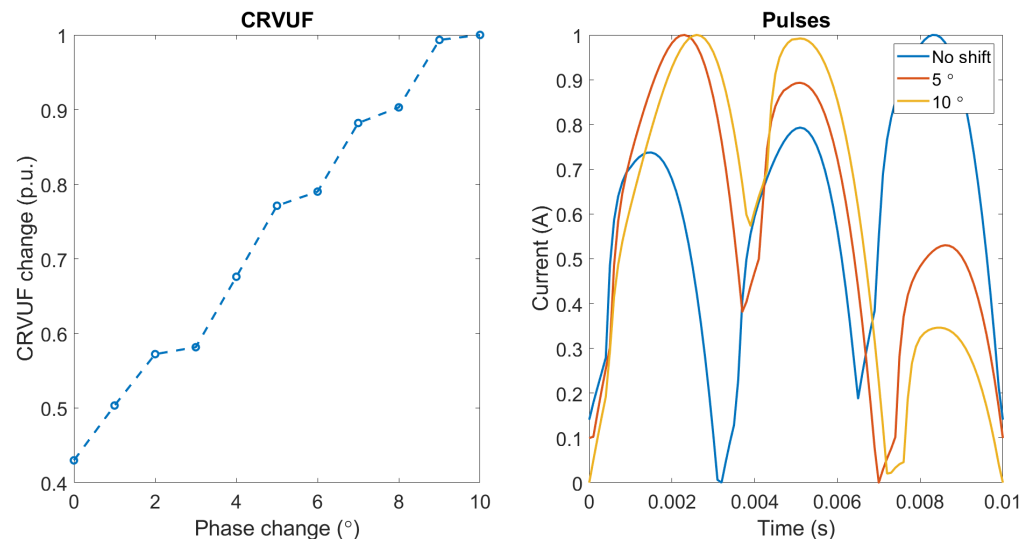


Figure 6. CRVUF in respect to phase shift in one of the supply voltages.

To check whether input signal filtering is required for CRVUF calculation, Signal to Noise Ratio (SNR) sensitivity is studied (Figure 7). Case 4 data was used to investigate unbalance indicator change. As can be seen in the following, CRVUF can be affected by noise as the error between the model and the measurement increases. Being prone to such discrepancies justifies the need to apply initial signal filtering to obtain satisfactory results.

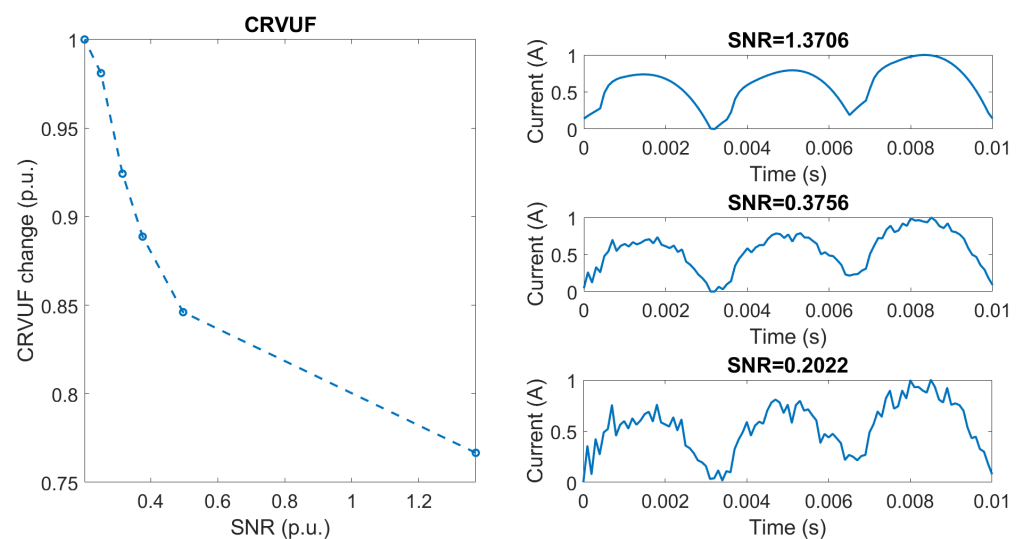


Figure 7. CRVUF in respect to SNR of measured I_1 .

During the lifetime of an AC/DC/AC converter, DC-link capacitance gradually drops due to the capacitor aging. The common threshold to consider is a 20% drop in capacitance value. The CRVUF value is almost unaffected by this phenomenon (Figure 8), changing less than 0.2% in response to a 20% capacitance drop. Further inspection of I_1 pulses reveals that despite DC-link capacitance change, pulses overlap even before normalization.

As the ambient temperature of the load may fluctuate, the load impedance can change. Symmetrical inductance change in the load was investigated during the simulation study (Figure 9). Three values of inductance were taken into consideration: the original one, 50% of it and 200%. The non-normalized I_1 value changes clearly, while normalized pulses have slight but noticeable differences. The change in CRVUF is less than 2.5% in response to a two times higher load inductance, proving its robustness to load change.

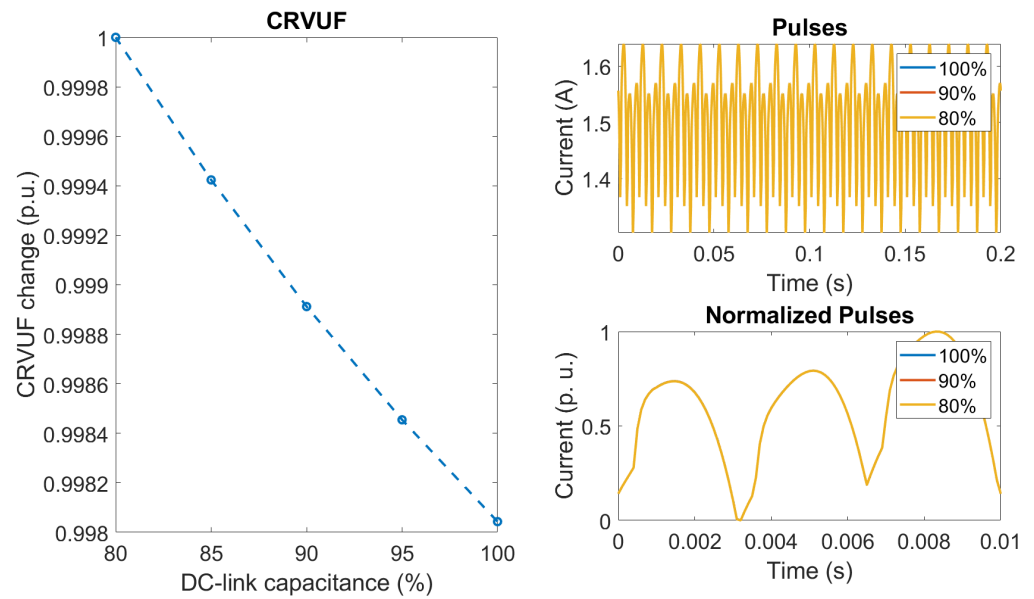


Figure 8. CRVUF and I_1 in response to DC-link capacitance change.

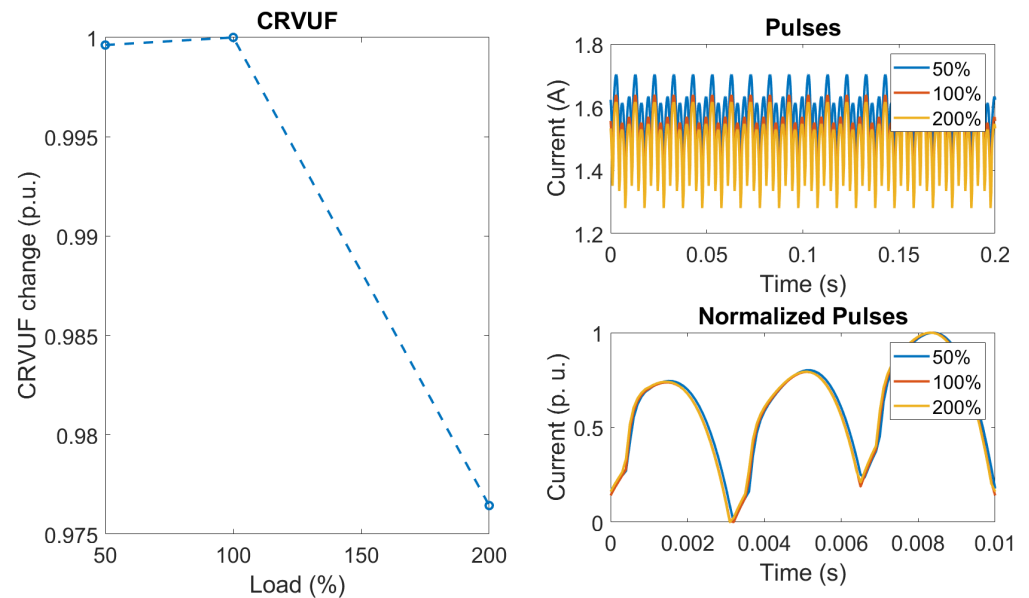


Figure 9. CRVUF and I_1 in response to inductance load change.

4. Experimental Verification

Experimental verification was conducted using a dedicated setup (Section 4.1). The power supply voltage values in cases used during the experimentation were the same as in Table 3.

4.1. Setup Description

The experimental setup has the same topology as presented in Figure 2. The load in the experimental case was a 1.5 kW induction motor. Phase voltages were adjusted to the desired unbalance case using autotransformers, one per each phase (Figure 10). The adjustment also caused the introduction of source impedance unbalance due to the nature of autotransformer operation. A current hall sensor was implemented to measure I_1 and 3 voltage sensors were used to record phase voltages to calculate VUF. Data were acquired at a frequency of 10 kHz via the dSpace 1103 board. This setup allowed us to replicate the same cases of unbalance that were presented in simulation validation in experimental conditions.

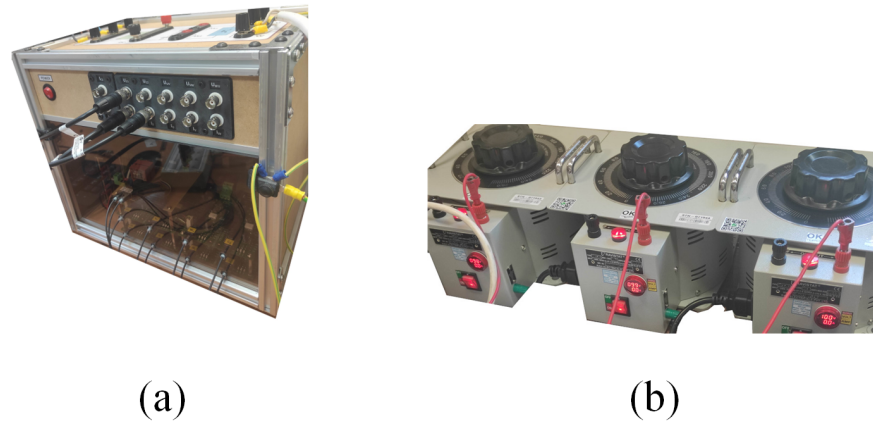


Figure 10. Experimental setup—AC/DC/AC converter with measuring ports (a) and three autotransformers for unbalance control (b).

Acquired signals underwent initial digital filtration using a low-pass filter with a time constant of 5×10^{-3} seconds and the following transfer function:

$$\frac{Y(s)}{X(s)} = \frac{1}{0.005s + 1} \quad (9)$$

where $Y(s)$ and $X(s)$ are the filter output and input Laplace transforms, while s is complex frequency-domain variable.

The control of the whole setup was achieved in Simulink (scalar control algorithm) and Control Desk (interface and data recording). The input from the computer was transferred to dSpace 1103, while the board provided control signals to the power converter controller to obtain the proper load operation. Figure 11 shows the connections and dependencies between each part of the experimental setup.

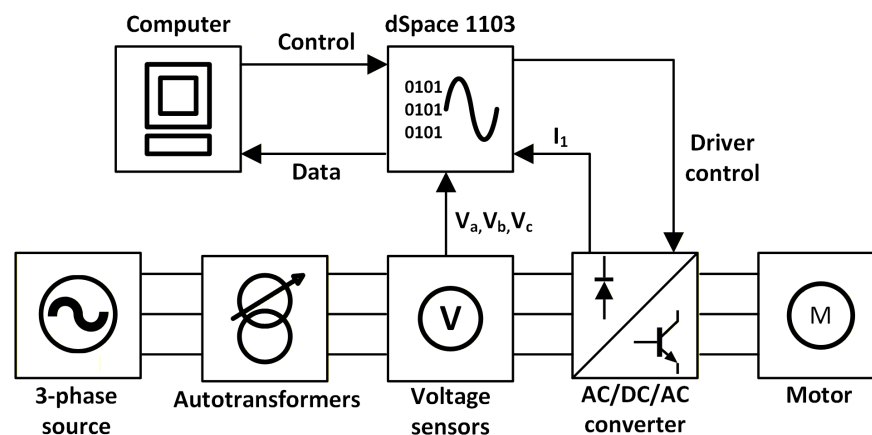


Figure 11. Experimental setup diagram.

The I_1 obtained from the experimental setup (Figure 12), even in a voltage-balanced state (all autotransformers set to 100 V), had uneven ripples due to the grid and load asymmetries. Moreover, additional phase shift imbalance could be noticed. That phenomenon was caused by uneven inductances of autotransformers while forcing voltage unbalance.

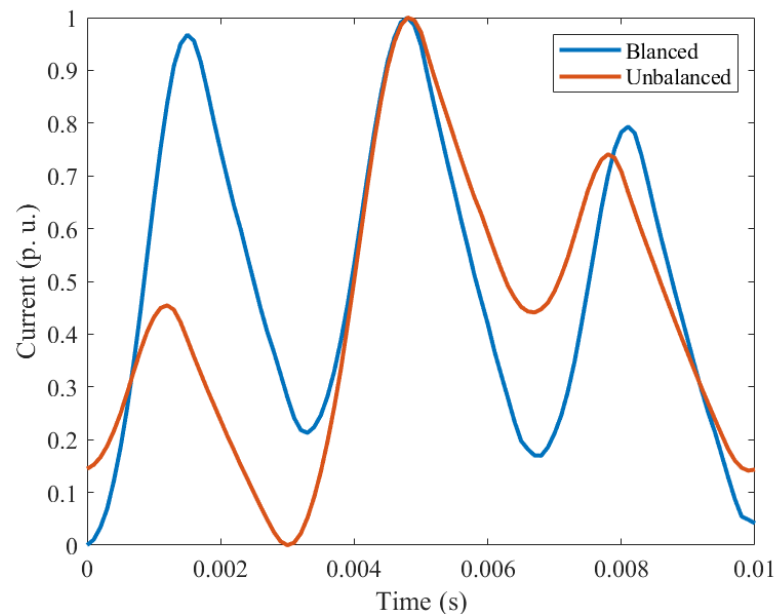


Figure 12. Comparison of reference and measured unbalance current.

4.2. Verification Results

Multiple measurements were made in order to properly verify the CRVUF method—for each unbalance case, 60 independent recordings were made at two different motor current frequencies (20 and 25 Hz). The motor rotational speed directly depends on stator current frequency. In Figure 13, three-pulse I_1 waveforms can be seen for the first six unbalance cases (Table 3). As the imbalance develops, the difference between current peaks becomes more pronounced. The different sequences of pulses are caused by the various time stamps at which sets were acquired. A similar trend as in U_{DC} of changing to a lower-frequency and higher-amplitude ripple (Figure 1) can be observed.

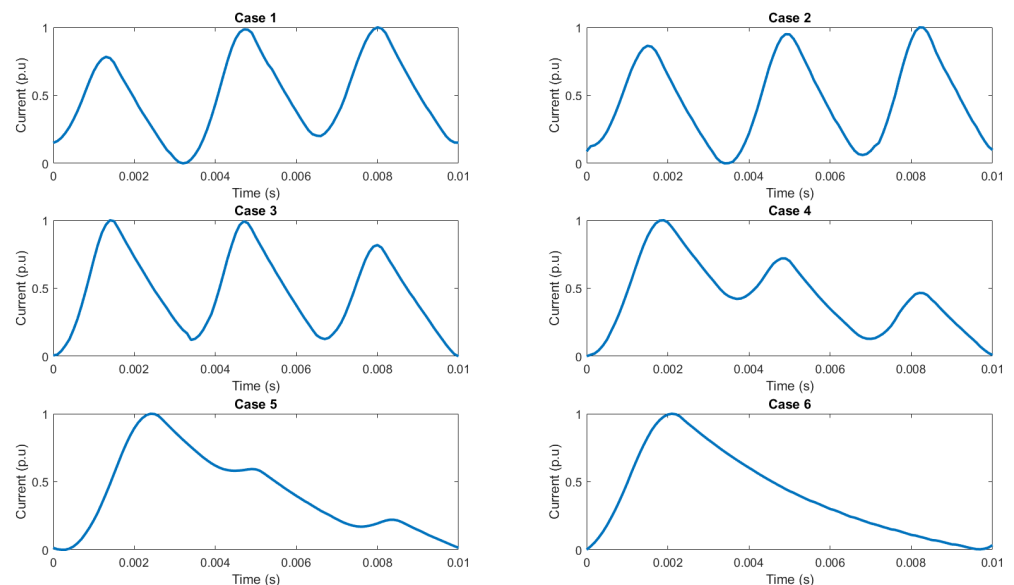


Figure 13. I_1 sets under different unbalance cases.

After obtaining the data, each I_1 ripple profile was calculated according to (8). The factor values presented in Figure 14 are the mean values of 60 independent calculations per unbalance case.

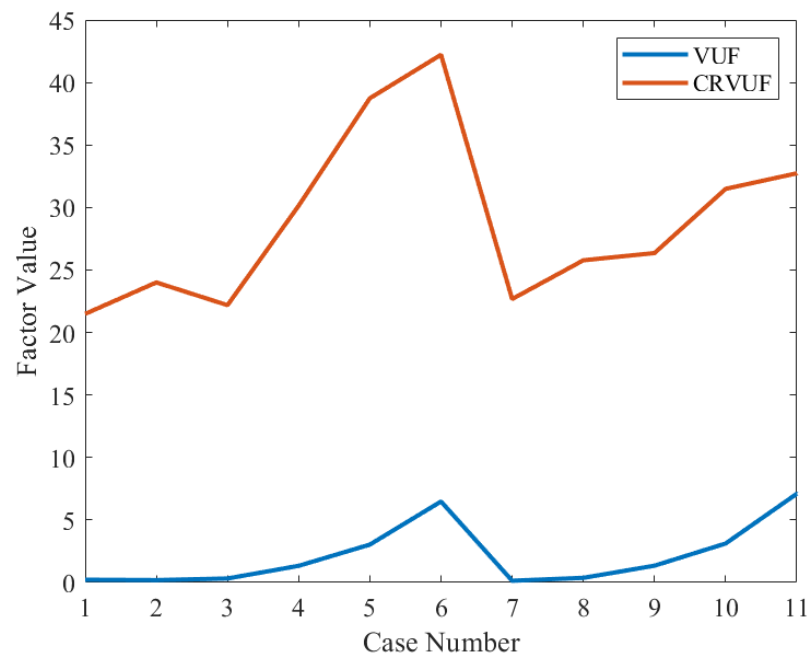


Figure 14. Comparison of CRVUF and VUF in different cases—experimental verification.

As can be seen in Figure 14, CRVUF has much higher values than VUF, which is due to the initial asymmetry in the balanced voltage state mentioned earlier. To compare these two factors more clearly, the CRVUF offset was removed and both unbalance indicators were scaled per unit, taking the highest value of each indicator as reference (Figure 15).

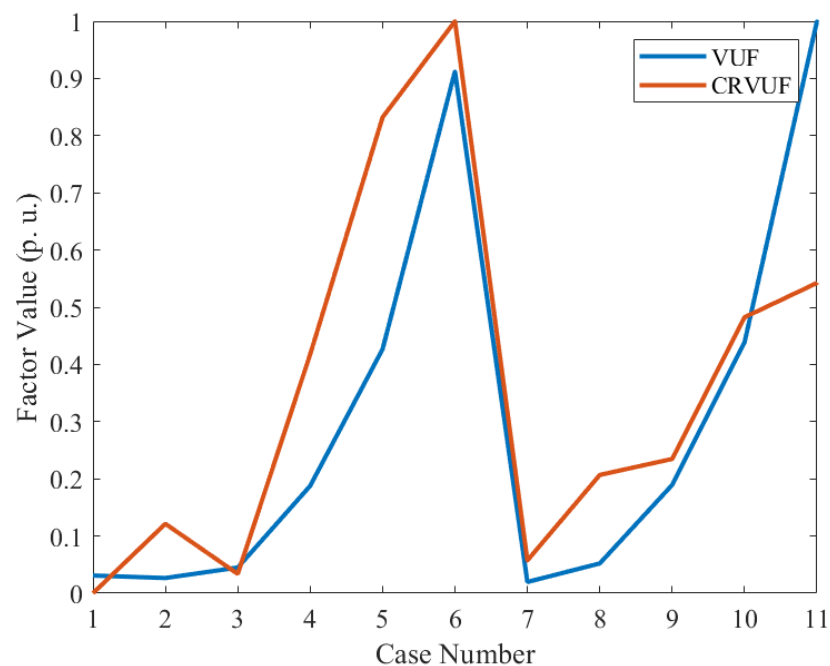


Figure 15. Comparison of CRVUF and VUF in different cases—experimental verification with amplitude and offset adjustment.

Both factors follow a similar trend; the most noticeable difference is between the 10th and 11th cases where VUF has a much higher dynamic increase than CRVUF. This is mostly related to the nature of the experimental setup. As the voltages in the supply change for each investigated case, the impedance of the autotransformers also varies, making the impedance of the lines uneven, which affects I_1 .

4.3. Statistical Analysis

For each set of 60 measurements per case, an interquartile range (IQR) study was performed. After readjusting VUF and CRVUF in a way similar to that in Figure 15, a visualization of the indicator value data was made (Figure 16). The CRVUF has a less stable output with a higher IQR (between 0.028–0.228 compared to 0.004–0.025 for VUF) and outlier count. The lower CRVUF performance comes with a tradeoff in reducing the number of sensors needed.

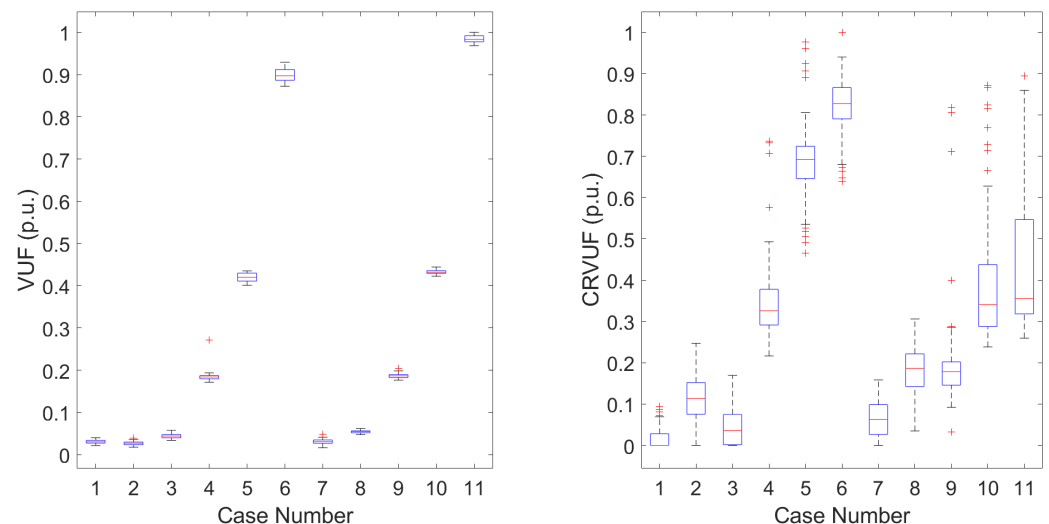


Figure 16. CRVUF and VUF comparison based on the factor value distribution with respect to the measured unbalance cases.

5. Conclusions

In this paper a novel DC-link current-based voltage unbalance monitoring method is presented. The CRVUF is obtained by referencing the balanced profile of I_1 that is generated with real measurements. The integer of ΔI (8) is considered the new unbalance factor—CRVUF. Using only one signal reduces the required number of sensors from three to one in comparison to the classical approach (6). In this work, the new usage of I_1 as the voltage unbalance indicator is introduced using the model comparison approach.

The similar nature of both VUF and CRVUF is shown in Figure 15, proving that methods based on I_1 as a phase voltage unbalance symptom can be used. The presented solution allows for power supply RMS and phase-imbalance detection using a single current sensor instead of the three used in classical voltage unbalance monitoring. Moreover, compared to DC-link voltage-focused approaches, current sensors are less costly options. In terms of implementation, the complexity of the presented solution and [13–15] are similar. In all of the cases, a singular additional sensor must be introduced if not present beforehand. The computational load of the method is low, in comparison to FFT [13] and wavelet transform or bispectral analysis [15], as it requires multiplication and subtraction for normalization, sine functions for reference generation and a trapezoidal integer for CRVUF calculation. However, the accuracy and noise robustness are lower than more computationally demanding solutions [15].

Because CRVUF is based on comparison with ideal waveforms, its results are less stable than typical assessment VUF and require initial filtering of I_1 to provide output at a satisfactory level, making it a low-cost auxiliary monitoring method.

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Abbreviations

The following abbreviations are used in this manuscript:

RMS	Root Mean Square
FFT	Fast Fourier Transform
VUF	Voltage Unbalance Factor
ESR	Equivalent Series Resistance
CRVUF	Current Ripple Voltage Unbalance Factor
SNR	Signal to Noise Ratio
IQR	Interquartile Range

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