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DIAGNOSIS OF VOLTAGE UNBALANCE STATE IN A SYSTEM WITH POWER CONVERTER

Stanisław OLISZEWSKI [1,*], Mateusz DYBKOWSKI [1]

[1] Wrocław University of Science and Technology, Poland
[*] Corresponding author, e-mail: stanislaw.oliszewski@pwr.edu.pl

Abstract

In the paper problem of power supply unbalance voltage states with the same Voltage Unbalance Factor (VUF) value for power converters is tackled. This factor is being used to assess the quality of power supply. There are many sources of voltage unbalance phenomenon such as system asymmetries and uneven distribution of demand throughout phases. Based on literature three unbalance states are presented: lines overvoltage, lines undervoltage and phase angle asymmetry. VUF value alone cannot provide information on the type of voltage unbalance state. Moreover, the same VUF percentage can be obtained for different amount of unbalanced phases. In this paper simulation experiments were conducted in order to obtain data of rectifier output voltage during different unbalance states with same VUF. Ripple, mean value and frequency components of said voltage were used in order to detect and categorise power supply voltage unbalance. Such approach does not require complex power quality measuring tools as power supply unbalance can be initially diagnosed using single voltage sensor.

Keywords: unbalanced voltage, power converter, power supply, voltage unbalance factor, diagnosis

List of Symbols/Acronyms

a – rotational vector (120°);
AC – Alternating Current;
DC – Direct Current;
FFT – Fast Fourier Transform;
IGBT – insulated-gate bipolar transistor;
PWM – Pulse Widith Modulation;
RL – resistance-inductance;
RMS – Root Mean Square;
U – Rectifier Output Voltage [V];
U_a, U_b, U_c – line-to-ground voltage [V];
U_{ab}, U_{bc}, U_{ca} – line-to-line voltage [V];
U_n – negative sequence voltage component [V];
U_p – positive sequence voltage component [V];
V – voltmeter;
VUF – Voltage Unbalance Factor [%];
Φ_a, Φ_b, Φ_c – phase shifts of power supply voltages [°].

1. INTRODUCTION

One of the most important aspects connected to the proper operation of three-phase power supplied systems is voltage unbalance regarding RMS of phase voltage and phase shift values.

Unbalance of power supply voltage is the cause of: power coefficient loss [1-4], DC-link voltage ripple amplification, induction motor torque ripple amplification [2, 3, 5, 6], system temperature rise [7-9], asymmetry of load phase currents [10]. This phenomenon may trigger single-phase rectifier operation (instead of its original three-phase operation) [11, 12]. Small voltage unbalance can be the source of big (in comparison) phase current unbalance [7]. Additionally phase voltage asymmetry influences the shortening of induction motor insulation lifespan [13].

Occurrence of voltage unbalance may be connected to: load asymmetry, dominating demand for single-phase load in the power grid [14], asymmetrical transformer winding, high impedance connectors [7], traction vehicle power supply [15, 16] and asymmetry of power grid line impedances [17].

Voltage unbalance appears in both transient and steady-state of power converter operation [18].

In the paper authors propose system diagnostic method based on mean value and ripple of rectifier output voltage. Additionally voltage unbalance detection method using frequency spectrum was proposed.

For research purposes models in Matlab Simulink environment were made – diode rectifier with RL load system and diode rectifier-inverter with three-phase RL load system. Simulations were conducted for different states of voltage unbalance and values of VUF in order to check universality of proposed methods. The advantage of proposed

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solution is that in order to utilize it only one sensor is required and it works for both DC and AC loads.

The main objective of this work is to design a diagnostic algorithm that will help in the voltage unbalance categorization. Moreover, this method should not have high costs of implementation – hence it only uses singular voltage sensor.

2. VOLTAGE UNBALANCE FACTOR

Unbalanced voltage is the phenomenon in the three-phase voltage system when voltage values and phase shifts are non-symmetrical [19]. Level of unbalance can be expressed via VUF with formulas below [20]:

$$VUF = \frac{U_n}{U_p} \cdot 100 \tag{1}$$

$$U_n = \frac{U_{ab} + a \cdot U_{bc} + a^2 \cdot U_{ca}}{3} \tag{2}$$

$$U_p = \frac{U_{ab} + a^2 \cdot U_{bc} + a \cdot U_{ca}}{3} \tag{3}$$

While calculating VUF it is possible to obtain the same percentage value for different voltage unbalance states. In this article data from [10] is used where following unbalance conditions are presented:

- 3Φ-UV – three undervoltage phases,
- 2Φ-UV – two undervoltage phases,
- 1Φ-UV – one undervoltage phase,
- 2Φ-A – two of the phase shifts are not 120° multiple,
- 1Φ-A – one of the phase shifts is not 120° multiple,
- 1Φ-OV – one overvoltage phase,
- 2Φ-OV – two overvoltage phases,
- 3Φ-OV – three overvoltage phases.

3. DIAGNOSIS OF POWER CONVERTER UNDER UNBALANCED VOLTAGE

3.1. Mathematical models

Two models of voltage converter system with 6-pulse diode rectifier were made using Matlab Simulink. First model has RL load (Figure 1) and second one represents system with voltage inverter and three-phase RL load (Figure 2). The inverter consists of IGBTs with antiparallel diodes. Power electronic and electrical components of systems were represented by objects from Simulink's Specialized Power Systems toolbox. Both power converters are supplied with three AC voltage sources which parameters are changed according to Table 1. Voltage sources are connected to rectifier with capacitance filter. Inverter was controlled using PWM method. Rectifier output voltage was measured.

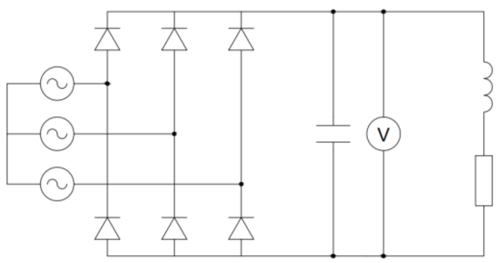

Fig. 1. System with RL load

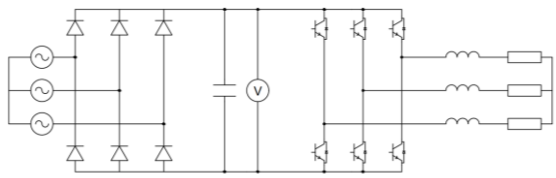

Fig. 2. System with three-phase RL load

Data from table above (Table 1.) was utilized as simulation parameters for power supply in purpose of discrimination of voltage unbalance state with the same VUF value.

The parameters of the circuits components are listed in the table below (Table 2).

Table 1. Phase voltages and shifts corresponding to VUF percentages [10]

Unbalance state	VUF [%]	U_a [V]	U_b [V]	U_c [V]	Φ_a [°]	Φ_b [°]	Φ_c [°]
-	0	127.0	127.0	127.0	0.0	240.0	120.0
3Φ-UV	4	110.0	112.7	125.0	0.0	240.0	120.0
2Φ-UV		111.8	114.3	127.0	0.0	240.0	120.0
1Φ-UV		112.4	127.0	127.0	0.0	240.0	120.0
2Φ-A		127.0	127.0	127.0	0.0	231.9	116.0
1Φ-A		127.0	127.0	127.0	0.0	240.0	113.1
1Φ-OV		142.9	127.0	127.0	0.0	240.0	120.0
2Φ-OV		145.9	138.3	127.0	0.0	240.0	120.0
3Φ-OV		148.2	139.7	129.0	0.0	240.0	120.0
3Φ-UV	6	103.2	107.2	125.0	0.0	240.0	120.0
2Φ-UV		105.0	108.6	127.0	0.0	240.0	120.0
1Φ-UV		105.4	127.0	127.0	0.0	240.0	120.0
2Φ-A		127.0	127.0	127.0	0.0	227.7	113.9
1Φ-A		127.0	127.0	127.0	0.0	240.0	109.7
1Φ-OV		151.3	127.0	127.0	0.0	240.0	120.0
2Φ-OV		156.5	144.7	127.0	0.0	240.0	120.0

3Φ-OV	159.0	146.2	129.0	0.0	240.0	120.0

Table 2. Circuits' key parameters

Parameter	Value
Load resistance [Ω]	100
Load inductance [mH]	5
Capacitor capacitance [µF]	1000
Transistor switching frequency [kHz]	10

3.2. Simulation details

Mathematical solver used for simulation is based on Euler method (ode1 in Simulink). Fixed step of $1 \cdot 10^{-7}$ seconds was introduced. Length of the simulated power converter operation is 0.04 seconds.

Time related and mean voltage values were recorded. After obtaining data, voltage values were used in FFT method in order to obtain frequency spectrum.

3.3. Simulation results

In this paper rectifier output voltage is analysed because it is the signal that is the least affected by load type change in comparison to the effects of voltage unbalance.

In order to recognise voltage unbalance state three properties of analysed signals were taken into account:

- low frequency components occurrence (up to 1 kHz),
- mean value,
- ripple level.

As the reference for ripple value healthy (balanced) voltage is considered. As for mean value, the reference level is when none of the phases are damaged. In every waveform figure (Fig 3. – Fig 14.) three subfigures can be seen. The top subfigure represents output voltage in the time domain while different amount of phases are in the fault condition. Middle one shows voltage mean value depending on the damaged phases count. Bottom subplot is the frequency spectrum of rectifier output voltage where amplitude per unit values are presented under different power supply improperly functioning phases count.

When power supply voltage unbalance is caused by undervoltage (Fig. 3 – Fig. 6), mean value of the rectifier output voltage is decreasing for the same VUF value as the damaged phase count increases.

In the frequency spectrum (1 kHz range) not only main frequency of 6-pulse rectified voltage (300 Hz) and it's harmonics are present while voltage unbalance occurs. Frequency component of 100 Hz can be noticed – it's value is higher than 300 Hz component under unbalanced power supply conditions. The increase of the ripple, in comparison to healthy case, occurs when system is subject to voltage unbalance.

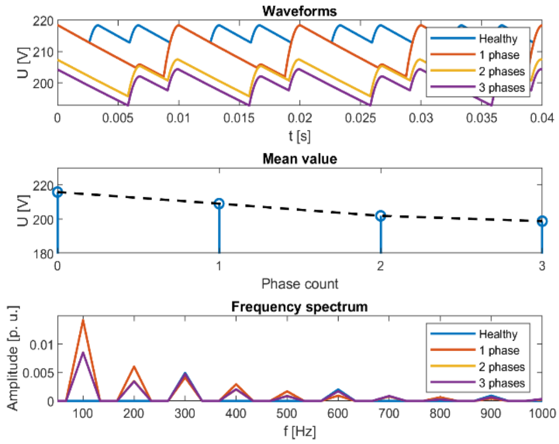

Fig. 3. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=4%, undervoltage)

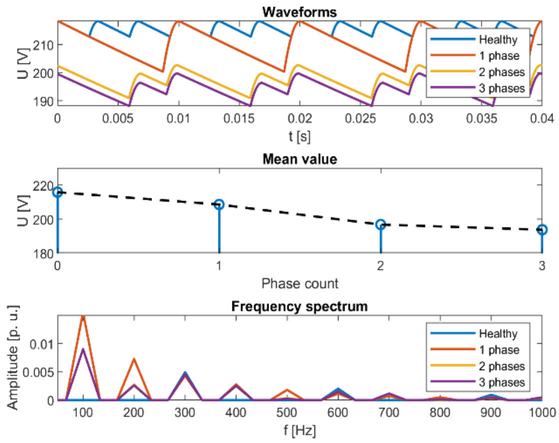

Fig. 4. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=6%, undervoltage)

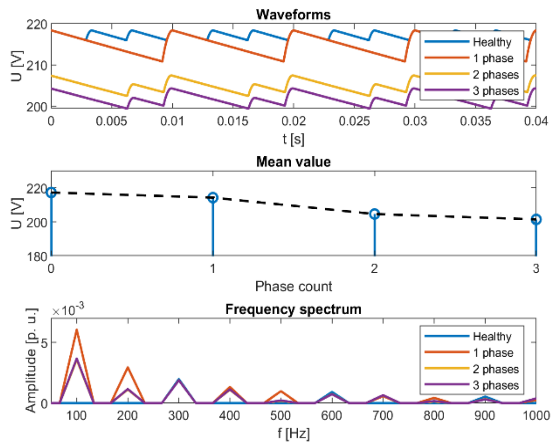

Fig. 5. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=4%, undervoltage)

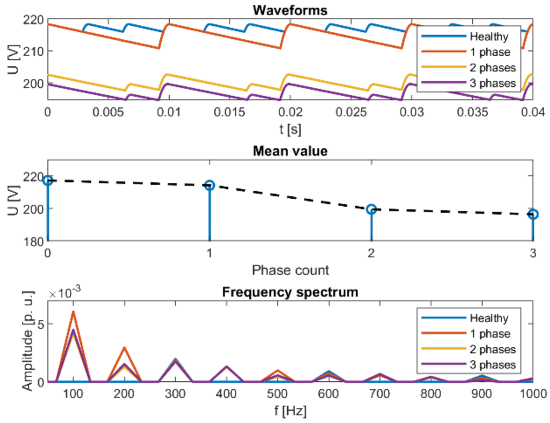

Fig. 6. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=6%, undervoltage)

Voltage unbalance due to overvoltage (Fig. 7 – Fig. 10) causes increase of mean value of the measured voltage signal. At the same VUF percentage, increase of output voltage is the bigger the higher count of damaged phases is. As in the case of undervoltage 100 Hz component has larger value than 300 Hz one in event of unbalance. Additionally, ripple of the rectifier output voltage, while being supplied from the unbalanced power source, is higher than in the healthy voltage converter system.

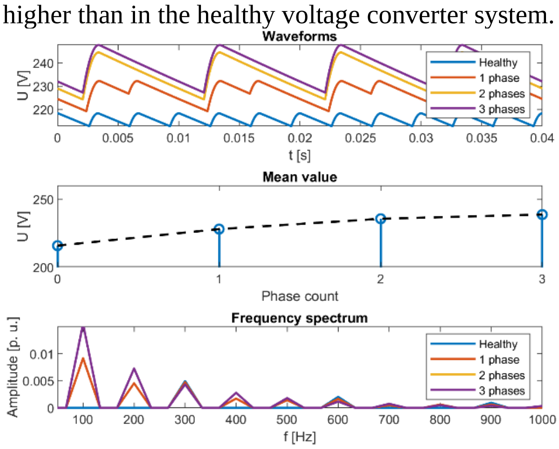

Fig. 7. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=4%, overvoltage)

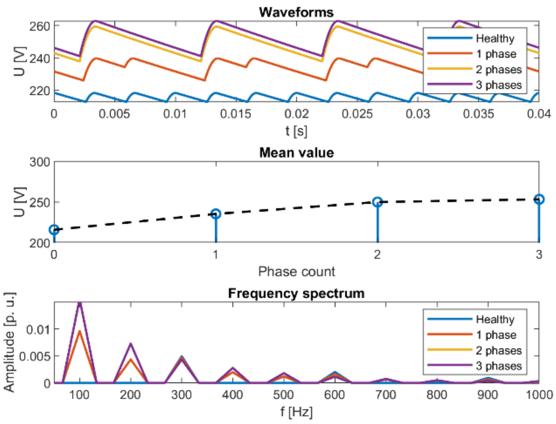

Fig. 8. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=6%, overvoltage)

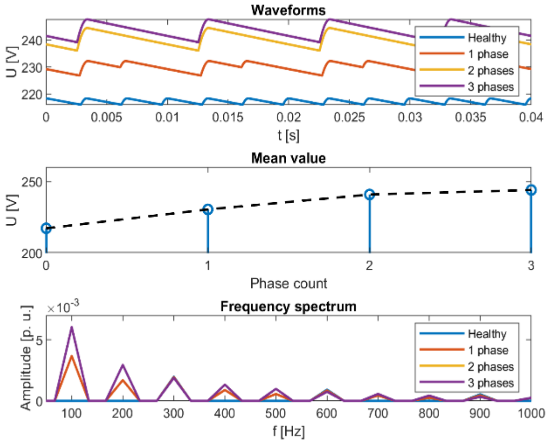

Fig. 9. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=4%, overvoltage)

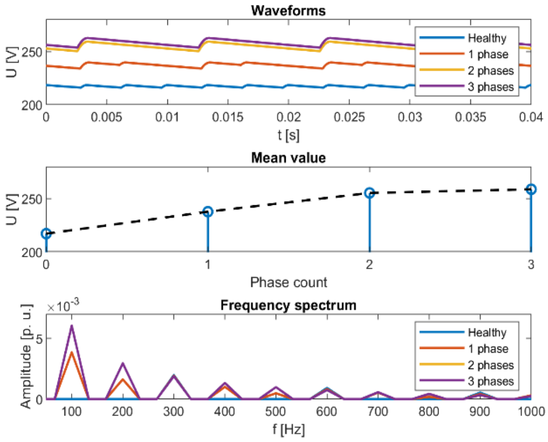

Fig. 10. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=6%, overvoltage)

Asymmetry of phase shifts that cause voltage unbalance (Fig. 11 – Fig. 14) do not have such big impact on output voltage mean value as cases mentioned before (undervoltage and overvoltage). However, voltage ripple increase can be observed – it's characteristic for this voltage unbalance state.
As in every considered state of the unbalance phenomenon, 100 Hz component has higher amplitude than main in the healthy condition 300 Hz component. It is worth noting that in the frequency spectrum both plots for cases with phase shift asymmetry are similar. The only noticeable difference is the mean value – it increases as the damaged phase count gets higher.

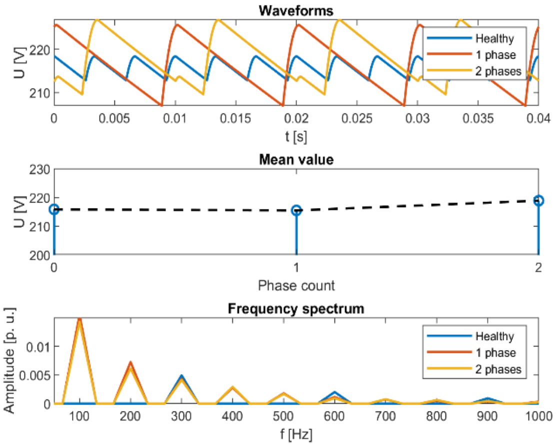

Fig. 11. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=4%, phase shift asymmetry)

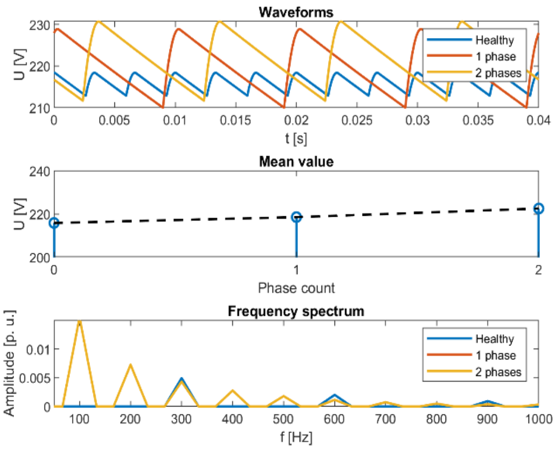

Fig. 12. Rectifier output voltage in relation to damaged power supply phase count (RL load, VUF=6%, phase shift asymmetry)

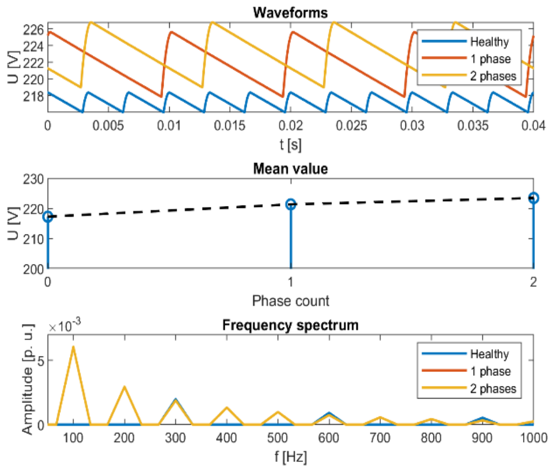

Fig. 13. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=4%, phase shift asymmetry)

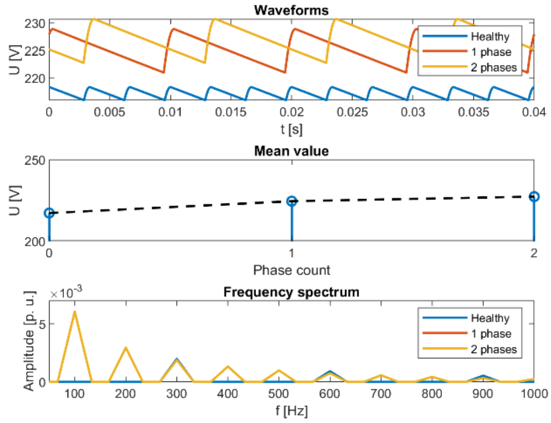

Fig. 14. Rectifier output voltage in relation to damaged power supply phase count (three-phase RL load, VUF=6%, phase shift asymmetry)

3.4. Proposed unbalance state recognition algorithm

Using the information obtained during the research, power supply voltage unbalance state recognition algorithm is proposed (Fig. 15).

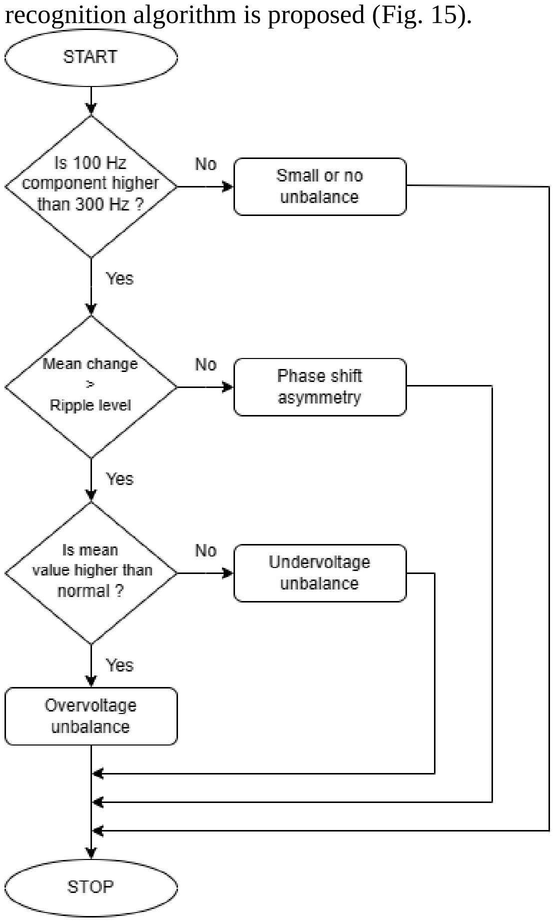

Fig. 15. Power supply voltage unbalance state recognition algorithm (for 50 Hz power supply)

In this algorithm the voltage unbalance state recognition procedure begins only when single-phase rectifier operation frequency component is dominant over the three-phase one. This step is necessary in order to ensure that unbalance occurs. Indicators of single-phase operation of a diode rectifier may not be present for VUF values below 4%.

Next step allows to assess whether unbalance type source comes from voltage amplitudes or phase shifts. If the rectified voltage ripple level is not lower than the mean value change, phase shift asymmetry of power supply voltages is present. In case of opposite situation (mean value change is higher than ripple level), voltage unbalance state may be connected to asymmetrical undervoltage or over voltage – further steps have to be taken in the recognition algorithm.

In the next part of algorithm rectifier output voltage mean value provides information useful for overvoltage and undervoltage discrimination. In the relation to normal (healthy) operation of power converter lower voltage mean value indicates asymmetrical undervoltage phenomenon. On the other hand, higher DC-link voltage mean value is linked to asymmetrical overvoltage.

After finishing voltage unbalance state assessment algorithm stops.

4. CONCLUSIONS

In the paper simulation experiments regarding analysis of voltage converter rectifier output voltage under different power supply voltage unbalance conditions were conducted. Using obtained output voltage data (ripple, mean value, frequency spectrum), voltage unbalance state recognition algorithm is proposed.

Voltage unbalance of three-phase power supply can be detected (regardless of unbalance state) by rectifier output voltage as the frequency component related to single-phase operation (100 Hz) has a higher value than three-phase operation component (300 Hz for 6-pulse rectifier) due to voltage converter being prone to operate in a single phase manner under unbalanced conditions. Detection of the phenomena does not require high sampling rate as indicators of it are in the low-frequency spectrum.

Analysis of rectifier output voltage ripple and mean value gives an opportunity to discriminate the voltage unbalance state – even with the same value of VUF. Power supply voltage unbalance states and their indicators are following:

- undervoltage – lower mean voltage value and ripple increase,
- overvoltage – higher mean voltage and ripple increase,
- phase shift asymmetry – ripple increase without (in comparison to ripple) big mean value changes.

Regarding conclusions above usage of frequency spectrum, mean and ripple values of rectifier output voltage allows to detect power supply voltage unbalance and categorize it in scope of unbalance state. The advantage of proposed method is that it only uses one voltage sensor.

Proper power supply voltage unbalance state recognition is beneficial in terms of maintaining power converters as it may shorten the time required for finding the source of phenomena in the system.

5. FURTHER RESEARCH AND DISCUSSION

Experimental station has to be designed and constructed in order to perform tests of proposed analysis methods. Such plant should consist of three independent AC voltage sources with possibility to control RMS value and phase shift of each. That setup could be used for various research regarding power supply unbalance of different systems.

As proven in the [10] VUF is insufficient for gauging the severity of power supply voltage unbalance state. Based on the analysis done in this paper information in frequency spectrum does not deliver constant relation to amount of phases affected by unbalance, for example – in the undervoltage case (figures from 3 to 6) 100 Hz component has higher value in 1-phase unbalance then in 3- and 2-phase one, whereas in the overvoltage 3-phase voltage unbalance has highest value of 100 Hz component. However, it could be possible to formulate a criterion considering voltage mean value absolute change and amount of unbalanced phases. Such criterion would provide information on the damaged phases count.

There is a risk of improper voltage unbalance state assessment in the situation when relatively small overvoltage or undervoltage causes significant rise in one-phase rectifier operation frequency component. That kind of occurrence may be mistakenly categorized as phase shift asymmetry.

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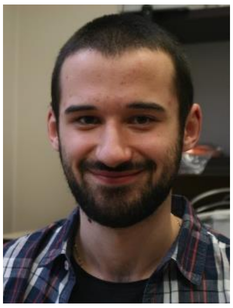

Stanisław OLISZEWSKI received the B.Sc. degree from the Faculty of Electrical Engineering, Wrocław, Poland in 2023. A the moment of writing this paper he is pursuing M.Sc. degree at faculty mentioned. His research interests include power electronics diagnostics, elastic shaft vibration damping and signal analysis.

Mateusz DYBKOWSKI received the M.Sc., Ph.D., and D.Sc. degrees from the Faculty of Electrical Engineering, Wrocław University of Technology, Wrocław, Poland, in 2004, 2008, and 2014, respectively. Since 2008, he has been a member of the academic staff with the Division of Electrical Drives Control, Department of Electrical Machines, Drives and Measurements, Wrocław University of Technology. He is the author or coauthor of more than 160 publications, one thesis, one monograph, 14 chapters in monographs, and more than 78 scientific papers in refereed conference proceedings and journals. His research interests include induction-motor drive control and state-variable estimations, control-theory applications in electrical drives, ac generators, digital-signal processors, and field-programmable gate array applications.