

Content

1 Motivation and aims	12
2 Adapted requirements	13
2.1 Definition of normal and fault operation	13
2.2 Fault clearance time and its components.....	15
2.3 Behaviour in fault operation (protection behaviour).....	15
2.3.1 Decoupling protection.....	15
2.3.2 Automatic final measures	16
2.4 Behaviour in critical system state (control behaviour)	16
3 Factors influencing the frequency	18
3.1 Frequency in electrical power engineering.....	18
3.1.1 General considerations on alternating voltages and three-phase systems	18
3.1.2 AC technology: two-phase measurement.....	19
3.1.3 Three-phase AC system: three-phase measurement	19
3.2 Digital measurement methods	20
3.2.1 Measurement of the period	20
3.2.2 Frequency measurement based on zero crossing detection.....	20
3.2.3 Frequency measurement based on phasors	21
3.2.4 Further examples of algorithms used for two-phase measurement.....	22
3.3 Causes of disturbances in frequency measurement	22
3.3.1 Non-linear components in the network	23
3.3.2 Magnetic and capacitive couplings	23
3.3.3 Step loads	23
3.3.4 Earth faults and short circuits	24
3.3.5 Switching operations	24
3.3.6 Frequency converter	24
3.4 Selection of measured quantities.....	25
3.5 Measurement requirements and measures against disturbance variables	25
4 Protection applications of the rate of change of frequency	26
4.1 Introduction and definitions.....	26
4.2 Measurement methods and algorithms.....	26
4.3 Applications of the ROCOF function	29
4.3.1 ROCOF application for adaptive underfrequency load shedding	29
4.3.2 Application for islanding detection and controlled islanding	31
4.3.3 Application limits	32
4.3.4 Typical setting values and modes of operation.....	33
4.4 Tests	36
5 Note on testing with harmonics	38
5.1 Principles.....	38
5.1.1 Rotating phasor and phase shift of fundamental and harmonic	38

5.1.2	Frequency change	38
5.2	Determination of the harmonic parameters	39
5.2.1	Accuracy check	39
5.2.2	Stability test	40
6	Blocking of frequency tripping	42
7	Simulation of under-frequency protection in case of load shedding	43
7.1	Objective	43
7.2	Principle of under-frequency protection measurement	43
7.3	Modeling and simulation	44
7.4	Behaviour with synthetically generated voltage characteristics	44
7.5	Behaviour with recorded fault data from different power systems	47
7.6	Behaviour with system model measurement data	49
7.7	Algorithm variants for frequency measurement	50
7.8	Conclusions	51
8	Real frequency responses	52
9	Recommendations for testing	57
9.1	Boundary conditions of the frequency protection test	57
9.1.1	Frequency jump or quasi-continuous frequency change	57
9.1.2	Frequency gradient	57
9.1.3	Impact of disturbance variables	58
9.1.4	Synthesis of voltage responses without instantaneous value jump after frequency change	59
9.1.5	Repetition of tests	61
9.1.6	Jumps in the frequency gradient	61
9.1.7	Pulse ramps	61
9.2	Recommendation for testing different frequency protection and ROCOF functions	61
9.2.1	Commissioning and repetition tests	61
9.2.2	Application tests of under-frequency and over-frequency protection	61
9.2.3	Additional active power determination	62
9.2.4	ROCOF function	62
9.2.5	Composite functions	62
9.3	Disturbance variables	62
9.3.1	Phase jump	62
9.3.2	Amplitude jump	63
9.3.3	Zero voltages	63
9.3.4	Harmonic and interharmonic oscillations	63
9.4	Recommendation for application testing (acceptance testing) of under-frequency protection for load shedding	63
9.4.1	Objectives of the application test	63
9.4.2	Distinction from IEC 60255-181	64
9.4.3	Specifications for the test sequence	64
9.4.4	Specification of test requirements	64

9.4.5	Blocking at undervoltage	65
9.4.6	Accuracy and tripping time without disturbances	66
9.4.7	Accuracy and tripping time for a phase jump	67
9.4.8	Accuracy and tripping time for a voltage jump	67
9.4.9	Accuracy and tripping time with harmonics and interharmonics.....	68
9.4.10	Accuracy and tripping time with superposed zero-sequence voltage.....	70
9.4.11	Repeat and commissioning tests.....	71
9.4.12	Overview and variants.....	71
9.4.13	Notes	71
10	Requirements for the circuit breaker	73
11	Frequency measurement of power converter	75
11.1	Power converter and frequency measurement	75
11.2	Simple PLL for frequency determination	75
11.3	PLL for frequency determination with unbalanced voltage.....	75
12	Outlook.....	78
13	Bibliography	80

Table of Figures

Figure 1	Necessary function blocks of the frequency measurement	12
Figure 2	Definition of the individual components of a fault clearance time	14
Figure 3	Representation of the harmonic sine oscillation as projection of the rotating complex phasor U	18
Figure 4	Representation of harmonic oscillation as rotating complex phasor	19
Figure 5	Example of the representation of a stationary high impedance earth fault in space vector representation	20
Figure 6	Frequency measurement based on zero crossing detection	21
Figure 7	Linear approximation for calculation of zero crossing	21
Figure 8	Result of the DFT: Phasor representation of the spectral line for the frequency f_0	22
Figure 9	Figure from IEC 60255-181 [3]	23
Figure 10	Amplitude jump	23
Figure 11	Phase jump	23
Figure 12	Earth fault in a resonant earthed system: Phase-to-earth voltages of an earth fault and mesh voltage u_{12} of an earth fault; multiple zero-crossings may occur	24
Figure 13	Eliminated short circuit [5]	24
Figure 14	Voltage with decaying direct component	24
Figure 15	Voltage reaction from frequency converter [5]	25
Figure 16	Principle of ROCOF determination	27
Figure 17	Example of ROCOF function	27
Figure 18	Frequency curve with ROCOF blocking and tripping processes	28
Figure 19	Block diagram showing the principle of frequency calculation	29
Figure 20	Frequency and df/dt -curves at a 21 % generation deficit in a 35 GW interconnected system with UFLS [6]	30
Figure 21	Possible basic structures of underfrequency load shedding with ROCOF	30
Figure 22	Adaptive underfrequency load shedding (acceleration of f < stage 1)	31
Figure 23	Stabilisation of ROCOF tripping characteristic with frequency deviation	32
Figure 24	Dynamic model of rotating masses and frequency dependence of loads	34
Figure 25	Power deficit at a given ROCOF setting as a function of response delay	34
Figure 26	Coordination of the response and release times of the link $f < \& ROCOF >$	35
Figure 27	Coordination of the $f < \& ROCOF >$ function with the underfrequency protection of the generating units	35
Figure 28	Example of adaptive UFLS	36
Figure 29	Phase-earth voltage characteristics; fundamental (50 Hz) superposed with 6 % fifth and 5 % seventh harmonics	40
Figure 30	Line-to-line voltage characteristics, as in Bild 29	40
Figure 31	Phase-earth voltage characteristics; fundamental (49,8 Hz) superposed with, for example, 20 % fifth and 20 % seventh harmonics	41
Figure 32	Line-to-line voltage characteristics, as in Bild 31	41

Figure 33	Phasor-based algorithm for frequency measurement.....	43
Figure 34	Model for sample under-frequency protection	44
Figure 35	Ramped frequency reduction with tripping at under-frequency.....	45
Figure 36	Ramped frequency reduction without tripping at under-frequency.....	45
Figure 37	Amplitude jump without triggering at the end of a frequency ramp	46
Figure 38	Phase jump with triggering at the end of a frequency ramp.....	46
Figure 39	Ramped frequency reduction with harmonics	47
Figure 40	Simulated frequency measurement for a disturbance in the European interconnected system on 10 January 2019.....	48
Figure 41	Simulated frequency measurement during the blackout in Turkey on 31 March 2015 [12].....	48
Figure 42	Simulated frequency measurement with fault data of a real relay "f2" at load shedding	49
Figure 43	Simulated frequency measurement during load shedding for recording a system model	50
Figure 44	Algorithm variants for frequency measurement with ramped frequency reduction together with harmonics and phase jump	51
Figure 45	Frequency responses of major disturbances, "IT – 28 September 2003" [13] and "DE – 4 November 2006" [14]	53
Figure 46	Frequency responses of major disturbances, "TR – 31 March 2015" [12] and "AU – 28 September 2016" [15]	54
Figure 47	Frequency responses at the time of disconnection of the Iberian Peninsula on 24 July 2021	55
Figure 48	Peak of the power frequency - frequency responses, system voltages and voltage angle difference.....	56
Figure 49	COMTRADE evaluation of Merida UFLS relay.....	56
Figure 50	Test for determining the tripping time; a) with continuous frequency change b) with frequency jump.....	57
Figure 51	Tripping time and measured tripping time with low frequency gradient; a) upper tolerance limit b) lower tolerance limit	58
Figure 52	Disturbance-free frequency jump	60
Figure 53	Frequency variation without phase adjustment	60
Figure 54	Frequency curve of the test – blockade at undervoltage, no unwanted operation.....	65
Figure 55	Frequency curve of the test – blockade at undervoltage, no incorrect operation.....	65
Figure 56	Frequency curve of the test – without disturbances, no unwanted operation.....	66
Figure 57	Frequency curve of the test – without disturbances, no incorrect operation	66
Figure 58	Frequency response of the test – phase jump, no unwanted operation.....	67
Figure 59	Frequency response of the test – phase jump, no incorrect operation	67
Figure 60	Frequency response of the test – voltage jump, no unwanted operation.....	68
Figure 61	Frequency response of the test – voltage jump, no incorrect operation.....	68
Figure 62	Frequency response of the test – (intermediate) harmonics, no unwanted operation.....	69

Figure 63	Frequency response of the test – (intermediate) harmonics, no incorrect operation.....	69
Figure 64	Frequency response of the test – superposed zero voltage, no unwanted operation.....	70
Figure 65	Frequency response of the test – superposed zero voltage, no incorrect operation.....	70
Figure 66	Path-time diagram of a typical medium-voltage vacuum circuit-breaker	73
Figure 67	Simple PLL	75
Figure 68	Bode diagram of a bandstop (notch filter)	76
Figure 69	PLL with notch filter for positive sequence component.....	77
Figure 70	Optimisation tasks with regard to shared system protection in terms of frequency measurement processing	78
Figure 71	Adaptive under-frequency load shedding (acceleration of f <-stage 1)	79

List of Tables

Table 1	Overview of relevant VDE application rules	13
Table 2	Tolerance band for normal grid operation according to VDE application rules	14
Table 3	Setting recommendation for frequency protection according to VDE application rules.....	15
Table 4	UFLS framework conditions	16
Table 5	Measures required for typical maximum active power jumps	36
Table 6	Maximum permissible harmonic distortion levels in public medium-voltage systems according to IEC 61000-2-12; $THD_{Max} = 8 \%$	39
Table 7	Test results without disturbance values	59
Table 8	Selected test results with additional phase jump	59
Table 9	Test requirements	64
Table 10	Overview of tests	72

List of Abbreviations

ADC	Analogue-to-digital converter
AR	Automatic reclosing
CB	circuit-breaker
CBLS	Contingency Based Load Shedding
DFT	Discrete Fourier Transform
ENTSO-E	European Network of Transmission System Operators
FFT	Fast-Fourier-Transformation
FIR	Finite Impulse Response
IIR	Infinite Impulse Response
LSE	Least Square Estimation
NC ER	Network Code Electricity Emergency and Restoration
NDZ	Non-Detection-Zone
PLL	Phase-Locked-Loop
PMU	Phasor Measurement Unit
RE	Renewable Energy
ROCOF	Rate of change of frequency
SFR	Simplified-Frequency-Response
THD	Total Harmonic Distortion
UFLS	Underfrequency load shedding

List of Formulas

df/dt	Frequency change (quasi-steady)
f	Operating frequency, momentary value
f_{nenn}	Nominal frequency 50 Hz, or rated frequency f_r
$f_{<}$	Setting value of the underfrequency protection
Δf	Amount of the required accuracy without disturbance variables: The underfrequency protection does not respond reliably at $f > (f_{<} + \Delta f)$, at $f < (f_{<} - \Delta f)$ it responds reliably if there are no disturbances.
Δf_{ob}	Amount of the required accuracy for tests for unwanted operation with disturbance variables: The underfrequency protection will not respond reliably at $f > (f_{<} + \Delta f_{\text{ob}})$ if disturbances are present.
Δf_{un}	Amount of required accuracy for tests for incorrect operation of protection with disturbance variables: The underfrequency protection responds reliably at $f > (f_{<} + \Delta f_{\text{un}})$ when disturbances are present.
H	Equivalent stored energy constant of all synchronous generating units
ΔP	Change in active power ($P_{\text{Verbrauch}} - P_{\text{Erzeugung}}$)
S_{nenn}	Nominal apparent power of the machines
t_{AFi}	Tripping time of the underfrequency protection at the i test. If ramps are used, then the tripping time is considered to be the time when the response value is first undershot until the OFF contact of the protection device is closed.
t_{AFmmax}	Maximum trip time with disturbances Maximum value of all measurements with disturbances
t_{AFomax}	Maximum trip time without disturbances Maximum value of all measurements without disturbances
t_{nach}	Time period during which no unwanted operation may occur
t_{vor}	Duration of pre-fault voltage during tests
U_B	The voltage value that has to be undershot for the underfrequency protection to be blocked.