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SECONDARY TESTING OF FREQUENCY PROTECTION FUNCTION IN ABB RELAYS FOR TOTAL 150 MS OPERATION TIME

School of Technology

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TIIVISTELMÄ

Tekijä	Teemu Salminen
Opinnäytetyön nimi	ABB:n releiden taajuussuojauksen toiminnon toisiokoestus, 150 ms kokonaissuojausajalle.
Vuosi	2025
Kieli	Englanti
Sivumäärä	45
Ohjaaja	Mikko Västi

Työssä tutkittiin suojareleen taajuussuojan toimintaa, kun verkkokoodin määrittelemä 150ms kokonaissuojaus aika on käytössä. Tavoitteena oli havainnoida taajuuden muutoksen vaikutus suojareleen taajuussuojan toimintaan ja toiminta-aikaan. Suojareleet koestettiin Omicronin Relay Test universe -ohjelmalla.

Työssä on käytetty yleisesti saatavilla olemassa olevia dokumentaatioita verkko-ohjesäännöistä ja suojareledokumentaatiosta.

Työn tuloksena oli tarkoitus tehdä tekninen ohjeistus, jossa olisi käyty läpi taajuussuojan konfiguroinnissa ja koestamisessa tarvittavat vaiheet. Tarvittavaan kokonaistoiminta-aikaan ei päästy kaikilla vaadituilla mittaustavoilla, joten ohjeistusta ei tehty.

Avainsanat suojarele, taajuussuoja, toisiokoestus

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ABSTRACT

Author	Teemu Salminen
Title	Secondary Testing of Frequency Protection Function in Abb Relays for Total 150 ms Operation Time
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The study examines the operation of the frequency protection function in ABB relays when the 150ms total protection time defined by the network code is in use. The aim was to observe the impact of frequency changes on the operation time of the relay's frequency protection. The relays were tested using Omicron's Relay Test Universe software.

The study utilized generally available documentation on network codes and relay documentation.

The intended result of the thesis was to create a technical guide for configuring and testing frequency protection if required response time meets the specified requirement. The required total response time was not achieved with all the required measurement methods.

Keywords protection relay, frequency protection, secondary testing

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TERMS AND ABBREVIATIONS

AIM	Analog input module
AUX	Auxiliary
A1RADR	Disturbance recorder analog channels
B1RBDR	Disturbance recorder digital channels
df/dt	Frequency rate-of-change
f	Frequency
f>	Overfrequency
f<	Underfrequency
Freq_DR	Measured frequency to disturbance recorder
FRPFRQ	Frequency protection function
Hz	Hertz
IEC	International Electrotechnical Commission
LDDF	Low frequency demand disconnection system
mHz	Millihertz
Mean	The mean is the arithmetic average of a set of values, or distribution. The mean is calculated by adding up the collected data and dividing by the total number of data points.
Median	The median is the middle number of the sampled data. The median number of a finite list of data can be found by arranging all the data from the lowest to the highest and picking the middle sample. If there is an even number of observations, then the median takes the average of the two middle values.
Mode	The mode of a data sample is the element that occurs most often in the collection. Where several values occur with the same frequency then the mode can be represented by more than one value.
NC ER	Network Code for Emergency and Restoration
ms	Millisecond
RDRE	Disturbance recorder

REX615	Freely configurable all-in-one protection relay
REX640	Freely configurable all-in-one protection relay
RoCoF	Rate of change of frequency
PHPTUV	The three-phase undervoltage protection function
PCM600	Protection and control IED manager
PSM	Power supply module
UTVTR	The phase and residual voltage preprocessing function
U3P	Three phase voltages in PCM600 application
Ux_RD	Phase voltage for disturbance recorder
VMMXU	Three-phase voltage measurement function

1 INTRODUCTION

This thesis was made for ABB Oy, Grid Components unit. The purpose of the thesis was to study the secondary testing of frequency protection in ABB relays. The analysis of European Network of Transmission System Operators for electricity has a recommendation of total measurement, and a tripping time of about 120ms must be considered for an underfrequency load shedding relay. To achieve this required protection time, the Fingrid network code has implemented a total operating time of 150ms, including a breaker delay.

The aim of this thesis was to study if it is possible to fulfill the Fingrid guide for the testing functionality of the underfrequency protection system. The thesis covers the secondary testing of frequency protection, including undervoltage and zero voltage lockout testing. The purpose was to pre-study if it would be possible to do a technical note for secondary testing frequency protection according to the Fingrid test requirements.

2 UNDERFREQUENCY PROTECTION IN DISTRIBUTION NETWORK

2.1 Underfrequency in Distribution Networks

Underfrequency in a distribution network occurs when the electrical frequency drops below the normal operating range, typically 50 Hz or 60 Hz, depending on the region. This can happen when there is an imbalance between power generation and demand, such as when the load exceeds the available generation capacity. To manage underfrequency situations, distribution networks often use underfrequency load shedding. This involves automatically disconnecting certain parts of the network to reduce the load and help stabilize the frequency. By shedding load, the system can prevent complete blackouts and maintain service to as many customers as possible. Underfrequency protection is crucial for ensuring the reliability and stability of the power system, especially with the increasing integration of distributed energy resources and renewable generation as windmills and solar power.

2.2 Inertia and Rate of Change of Frequency in Distribution Networks

Power systems these days are in the middle of a transition. A general process of decarbonization and phasing out traditional power plants has been started. Traditional plants are based on large turbo or hydro generators and due to their characteristics, they make a significant amount of inertia to power systems. New generation solar or wind power is connected to the grid through power electronic; therefore, no additional inertia is added to the power system. This is causing a rate of change of the frequency increasing and system security will be endangered (see Figure 1).

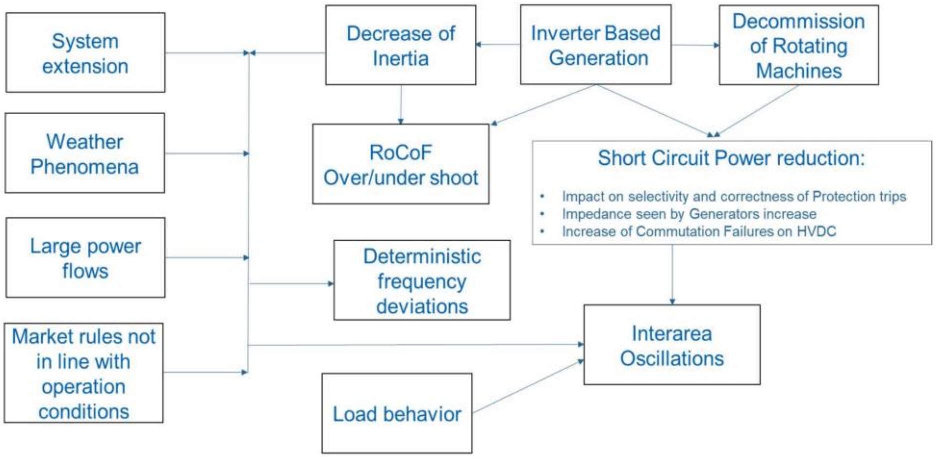


Figure 1. Network interaction to rate of change of frequency (Entsoe 2022 p.5)

The European network of transmission systems operators for electricity has studied different imbalance situations in distribution networks. (see Figure 2) These can be arranged into two groups. Systems survived in a stable way, or entire system or parts of it were blacked out. As a key factor in imbalance events, in those cases where RoCoF values were lower than 0,5Hz/s, all defense systems were able to trigger. In cases where RoCoF values were over 1Hz/s, all these events ended with fast grid collapse. This limit is related to the minimum time to measure frequency in a stable and secure way. (Entsoe 2022 p.43)

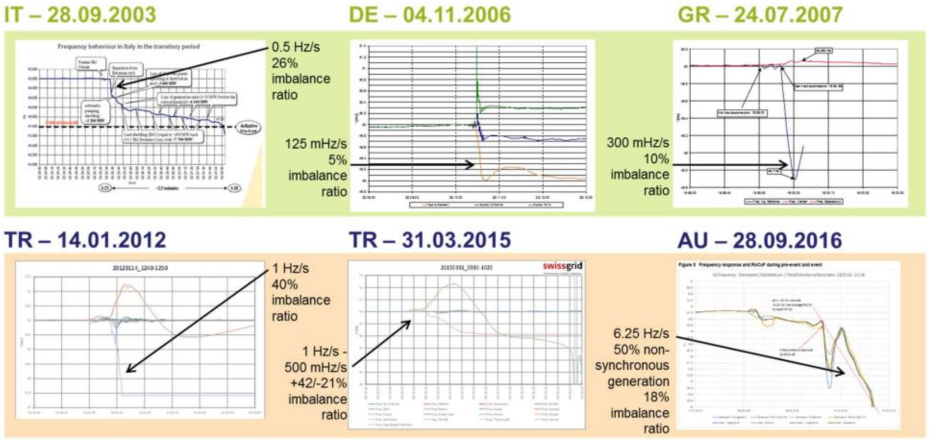

IT – 28.09.2003
DE – 04.11.2006
GR – 24.07.2007
0.5 Hz/s 26% imbalance ratio
125 mHz/s 5% imbalance ratio
300 mHz/s 10% imbalance ratio
TR – 14.01.2012
TR – 31.03.2015
AU – 28.09.2016
1 Hz/s 40% imbalance ratio
1 Hz/s - 500 mHz/s +42/-21% imbalance ratio
6.25 Hz/s 50% non-synchronous generation 18% imbalance ratio

Figure 2. Serious events and their RoCoF (Entsoe 2022 p.43)

2.3 Underfrequency Protection in Finland

In Finland, Fingrid is the national electricity transmission grid operator and is responsible for implementing the practical measures required by the Network Code for Emergency and Restoration (NC ER). One of these measures includes the automatic low frequency demand disconnection system (LFDD). LFDD is implemented to prevent the system frequency from dropping too low, thereby avoiding a total blackout in the transmission grid network. In Finland, 30% of the country's electric consumption is included in the LFDD system, allowing for potential disconnection from the network to prevent the frequency from dropping below 48 Hz. (Fingrid, 2019)

2.4 Requirements to Underfrequency Protection from the Fingrid Network Code

Underfrequency protection must operate under 0.15 seconds after the frequency has dropped below the critical point. This time also includes delays of the relays and circuit breakers. The operation time for the circuit breaker is assumed to be 40ms in the calculations of protecting times. Also, the underfrequency protection must be able to operate down to a voltage level of 0.6...0.4 of the nominal phase voltage. The Network code defines five different frequency levels for operation of underfrequency protection. In the first four steps, 5% of the load is dropped and in the fifth step 10% as shown in Table 1. There are two possible ways for distribution network companies to achieve the required 30% load reduction. In a larger distribution network company, the reduction can be distributed to multiple substations when frequency steps can reduce loads as needed to achieve the mandatory percentage level. In this case it is not required to have all five frequency steps in use at all substations. For smaller distribution network companies, it is possible to have only a few frequency steps but 30% of loads must be reduced after the last step. Trip signals for these different protection steps can be sent to other cubicles locally by hard-wired or remote using IEC 61850 or other communication protocols applied in substation automation. (Fingrid, 2019)

Table 1. Protection stage steps

Protection stage	**f(Hz)**	**Max delay(s)**	**f(Hz)*n**	**% from total load**
1	48.8	0.15	0.976	5
2	48.6	0.15	0.972	5
3	48.4	0.15	0.968	5
4	48.2	0.15	0.964	5
5	48	0.15	0.96	10

2.5 Fingrid Guide for the Testing Functionality of the Underfrequency Protection System

The testing requirement for the underfrequency protection system applies to distribution network and high-voltage distribution network operators, as well as electricity consumers, designated as significant in terms of the system's contingency plan. The functionality of the underfrequency protection system must be tested at least every 6 years. Distribution network companies and other participants in the underfrequency protection must submit test reports to Fingrid, detailing the measurement results for all frequency stages used at the consumption site. At a minimum, a substation-specific summary report must be provided.

The tests must verify the following for each relay in the system:

a) Operating time without triggering the circuit breaker,

b) Activation and recovery frequency,

c) Frequency limits and operating times for all operational stages,

d) Functionality of all contacts and inputs in use in the relay,

e) Correct operation in undervoltage conditions,

f) Zero voltage lockout, if implemented, and

g) Accuracy of indications.

The total operating time of the underfrequency protection must not exceed 150ms. Therefore, the operating time of the relay should be around 100ms. The operating time is tested from the terminals leading to the circuit breaker coils (including trip auxiliary relays). The operating time is tested with two different step frequency changes. The operation in a large frequency change is tested with a step change from nominal frequency → relay trip frequency - 0.05 Hz. The operation in a slow frequency change is tested with a step change of 0.1 Hz: relay trip frequency + 0.05 Hz → relay trip frequency - 0.05 Hz. For example, if the setting is 48.50 Hz, then change 1: 50.00 Hz → 48.45 Hz and change 2: 48.55 Hz → 48.45 Hz. (Fingrid 2019)

2.6 Implementation and Challenges of Frequency Protection with FRPFRQ Protection Block

The frequency of network is typically measured from the incomer or the main busbar of the switchgear from phase voltages using traditional voltage transformers or voltage sensors. When transformers or sensors are connected directly to protection relays, the configuration of all needed parameters to UTVTR Phase and residual voltage preprocessing function block is required. Also, the use of IEC61850-9-2 sampled values is possible as an input signal to UTVTR Phase and residual voltage preprocessing function block.

Frequency protection FRPFRQ has three different frequency protection functions which can be used individually or together with some limitations. These three protection functions are underfrequency (f>), overfrequency (f<) and frequency rate-of-change protection (df/dt). For this type of protection, underfrequency is used due to the protection steps needed in the disconnection of the load when the network frequency is dropping, as described in the network code. Measured values needed for the FRPFRQ function block is processed in the UTVTR function block. At least one phase or phase -to -phase voltage channels need to be in use for frequency protection. Figure 3 shows the module diagram of the FRPFRQ function. (ABB 2025 technical manual)

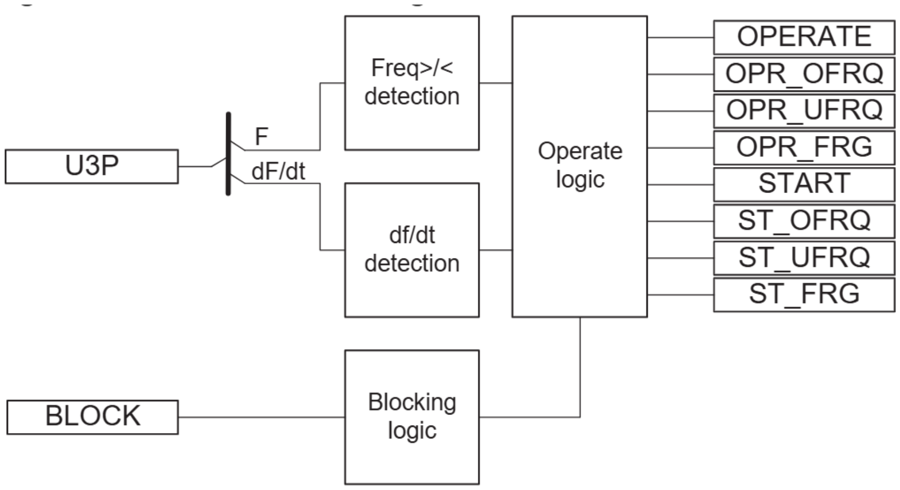


Figure 3. FRPFRQ Operation principle (ABB, 2025)

Achieving a total maximum protection time of 150ms, including relay and breaker operating times, is challenging because the FRPFRQ protection function has a minimum operating time of 80ms. The typical operating time of the breaker must be included in the total protection time. A 40ms operating time is typically used in calculations. This typical operating time value is provided in the Fingrid document. (Fingrid 2019 p.1)

3 TESTING UNDERFREQUENCY PROTECTION FUNCTION

3.1 Testing Underfrequency Protection According to the Standard IEC 60255-181

The IEC 60255 standard is intended to standardize functional requirements for frequency protection. IEC 60255 standard describes how relays must be type tested and how test results should be published. Generally, the tests described in the document are not directly intended for use in yearly routine tests or during the commissioning of relays.

From IEC 60255 standard two selected tests were chosen for this study. To study the fast underfrequency protection test, the selected test would be a pseudo-continuous frequency ramp 6.2.1.1, test method based on a sudden change in frequency 6.3.2.1. These tests from the standard were chosen for testing due to their suitability to meet the Fingrid network code secondary test guide. The pseudo-continuous frequency ramp was used in tests to determine activation and recovery frequencies. Protection operate times were tested using a sudden frequency change. (IEC60255-181 p.24)

3.2 Trip Time Measurement with Pseudo-continuous Frequency Ramp

In this test type injected phase is based on continuous frequency ramp (see Figure 4). The initial start frequency to the ramp was 5 times the declared accuracy of relay. For example, in REX640 the declared accuracy of frequency protection is +-10mHz. For the over-frequency function, a reported accuracy of ±10 mHz means the initial frequency is Gs−0.05 Hz

The duration of each ramp step was 500ms. During the transition between frequency steps, the injected signal was continuous, with no step change in the phase angle or magnitude except for the frequency. (IEC60255-181 p.28)

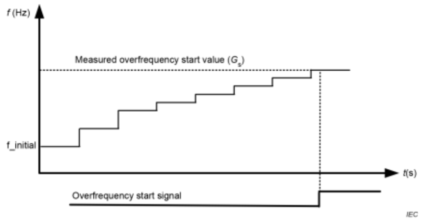


Figure 4. trip time measurement with pseudo-continuous frequency ramp. (IEC60255-181 p.28)

3.3 Trip Time Measurement with Sudden Frequency Change

The sudden frequency change test was based on two different frequency steps with a sudden change (see Figure 5). The start value in the large frequency chance was 50Hz and in slow frequency chance 48,85Hz. The end test point values were in both cases 48,75Hz. This testing was done to measure the trip time with different frequencies. Start and trip time was measured from between the instant when the frequency changes. The injected signal was without discontinuity in the voltage waveform, except in its frequency during testing. (IEC60255-181 p.44)

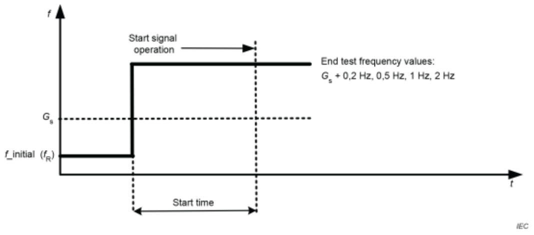
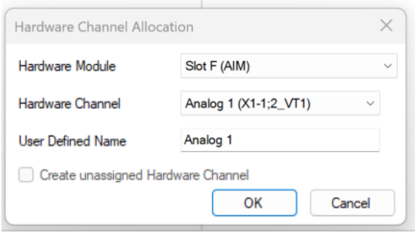


Figure 5. Trip time measurement with sudden frequency change. (IEC60255-181 p.44)

4 TOOLS, SETTINGS AND CONFIGURATION FOR TESTING UNDERFREQUENCY PROTECTION WITH ABB PROTECTION RELAYS

4.1 Application Configuration for REX640 and REX615 in PCM600

In application configuration, the used analog input voltage channels were determined first, shown in Figure 6 and Figure 7. Hardware channel allocation is needed for all inputs to select used hardware module, hardware channel and define name if need.



Hardware Channel Allocation

Hardware Module: Slot F (AIM)

Hardware Channel: Analog 1 (X1-1;2_VT1)

User Defined Name: Analog 1

☐ Create unassigned Hardware Channel

Figure 6. Hardware channel allocation REX640.

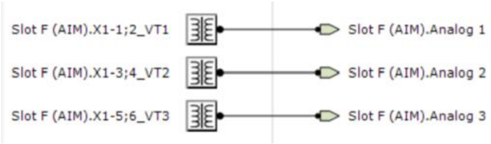


Figure 7. Hardware channels connected to variables.

The UTVTR function block is for phase and residual voltage preprocessing. As input for this function block, the analog input from AIM-module was used but also IEC 61850-9-2 sampled values can be used. The output data from the U3P output is needed for frequency protection function FRPFRQ blocks. The hardware channels were connected to the UL1-UL3 input using variables. Ux_DR and FREQ_DR outputs were connected to disturbance recorder as shown in Figure 8.

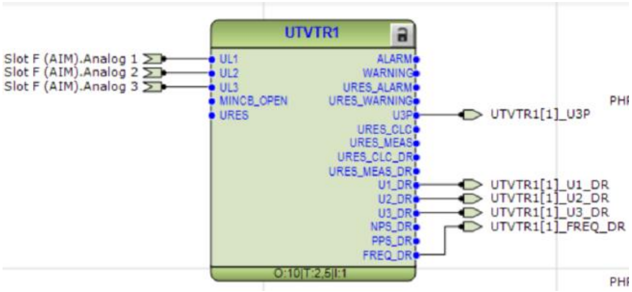


Figure 8. UTVTR phase and residual voltage preprocessing function block.

The operate signal output of the FRPFRQ frequency protection block was connected directly to the input of operate TRPPTRC master trip function block, shown in Figure 9. Operate, start and trip signals were connected to output relays to measure operating and start times using Omicron CMC 256plus. The undervoltage protection was connected to block the input of protection function to prevent the faulty operation of the protection in undervoltage situation

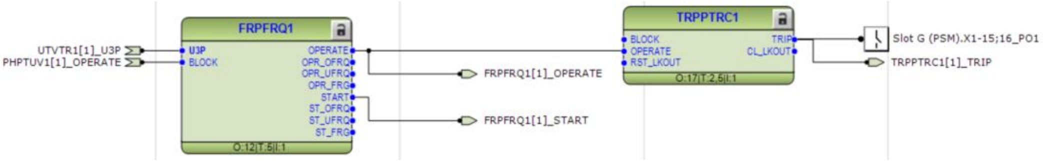


Figure 9. FRPFRQ frequency protection and TRPPTRC master trip function block.

The PHPTUV1 undervoltage protection function block was used to block the frequency protection function when voltage levels are under the determined lower value to reduce the risk of the malfunction of frequency protection. See Figure 10.

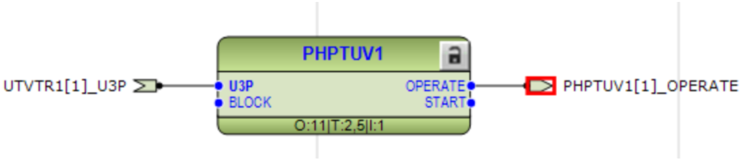


Figure 10. PHPTUV1 undervoltage protection function block

The disturbance recorder RDRE was needed to capture and analyze signals recorded by relay. A1RADR is the analog disturbance recorder, which captures and records analog signals injected to relay. B1RBDR is the binary disturbance recorder, records binary signals, such as relay operations and binary status changes. A RDRE function block is needed for operation. Monitored analog signals are connected from the UTVTR function block to the AxRADR disturbance recorder function block and the needed binary signals to BxRBDR disturbance recorder function block shown in Figure 11.

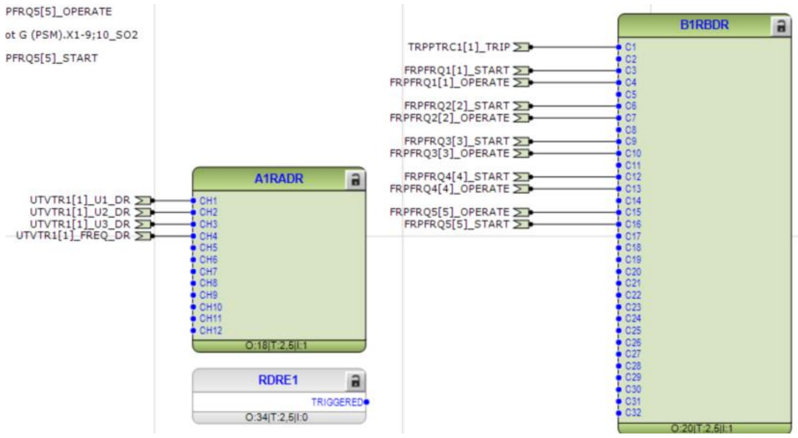


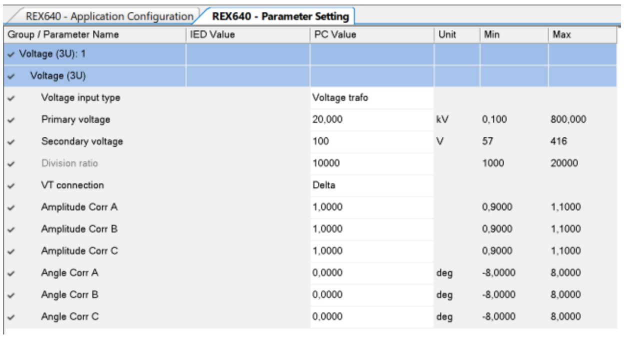
Figure 11. Disturbance recorder function blocks RDRE, A1RADR and B1RBDR.

4.2 Parameter Settings

The parameters for testing UTVTR are given in Figure 12.

The testing parameters used in the example are in UTVTR as follows:

- **Voltage input** = Voltage transformers
- **Primary voltage** = 20000V
- **Secondary voltage** = 100V
- **VT connection** = Delta



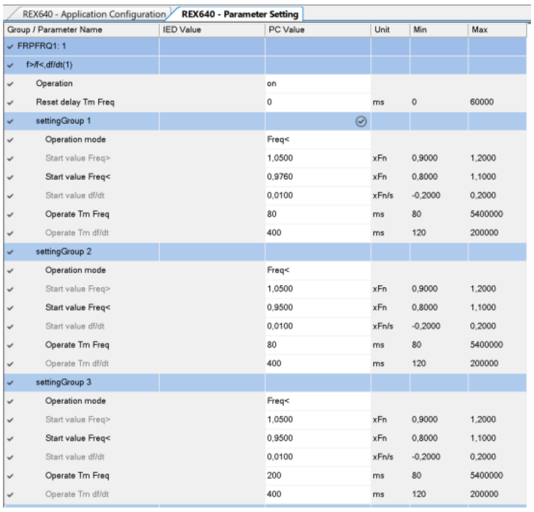
Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
✓ Voltage (3U): 1					
✓ Voltage (3U)					
✓ Voltage input type		Voltage trafo			
✓ Primary voltage		20,000	kV	0,100	800,000
✓ Secondary voltage		100	V	57	416
✓ Division ratio		10000		1000	20000
✓ VT connection		Delta			
✓ Amplitude Corr A		1,0000		0,9000	1,1000
✓ Amplitude Corr B		1,0000		0,9000	1,1000
✓ Amplitude Corr C		1,0000		0,9000	1,1000
✓ Angle Corr A		0,0000	deg	-8,0000	8,0000
✓ Angle Corr B		0,0000	deg	-8,0000	8,0000
✓ Angle Corr C		0,0000	deg	-8,0000	8,0000

Figure 12. Parameters used for testing UTVTR.

The parameters for testing FRPFRQ are given in Figure 13**.**

The testing parameters used in the example are in FRPFRQ as follows:

- **Operation mode** = Freq< (Undervoltage)
- **Start value Freq<** = 0.9760 (48,80Hz)
- **Operation time Freq** = 80ms
- **Reset delay time Freq** = 0ms



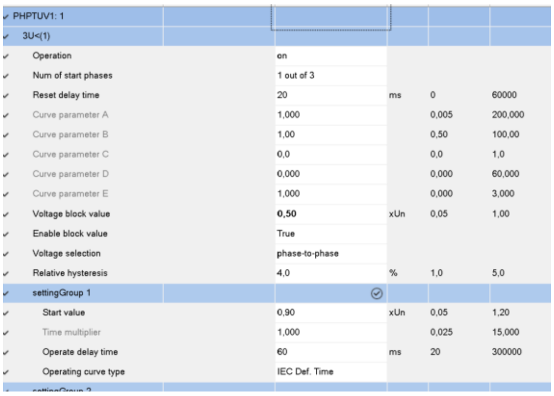
Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
FRPFRQ1: 1					
f>/f<,df/dt(1)					
Operation		on			
Reset delay Tm Freq		0	ms	0	60000
settingGroup 1					
Operation mode		Freq<			
Start value Freq>		1,0500	xFn	0,9000	1,2000
Start value Freq<		0,9760	xFn	0,8000	1,1000
Start value df/dt		0,0100	xFn/s	-0,2000	0,2000
Operate Tm Freq		80	ms	80	5400000
Operate Tm df/dt		400	ms	120	200000
settingGroup 2					
Operation mode		Freq<			
Start value Freq>		1,0500	xFn	0,9000	1,2000
Start value Freq<		0,9500	xFn	0,8000	1,1000
Start value df/dt		0,0100	xFn/s	-0,2000	0,2000
Operate Tm Freq		80	ms	80	5400000
Operate Tm df/dt		400	ms	120	200000
settingGroup 3					
Operation mode		Freq<			
Start value Freq>		1,0500	xFn	0,9000	1,2000
Start value Freq<		0,9500	xFn	0,8000	1,1000
Start value df/dt		0,0100	xFn/s	-0,2000	0,2000
Operate Tm Freq		200	ms	80	5400000
Operate Tm df/dt		400	ms	120	200000

Figure 13. Parameter used for testing FRPFRQ

The parameters for testing PHPTUV are given in Figure 14**.**

The testing parameters used in the example are in PHPTUV as follows:

- **Num of start phases** =1 out of 3
- **Start value Freq<** = 0.60 (60V)
- **Operation time delay** = 60ms
- **Reset delay time Freq** = 20ms



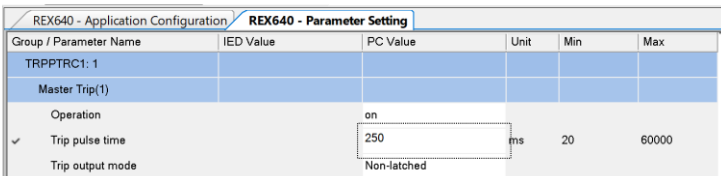
PHPTUV1: 1					
3U<(1)					
Operation		on			
Num of start phases		1 out of 3			
Reset delay time		20	ms	0	60000
Curve parameter A		1,000		0,005	200,000
Curve parameter B		1,00		0,50	100,00
Curve parameter C		0,0		0,0	1,0
Curve parameter D		0,000		0,000	60,000
Curve parameter E		1,000		0,000	3,000
Voltage block value		**0,50**	xUn	0,05	1,00
Enable block value		True			
Voltage selection		phase-to-phase			
Relative hysteresis		4,0	%	1,0	5,0
settingGroup 1					
Start value		0,90	xUn	0,05	1,20
Time multiplier		1,000		0,025	15,000
Operate delay time		60	ms	20	300000
Operating curve type		IEC Def. Time			

Figure 14. Parameters used for testing PHPTUV

The parameters for testing TRPPTRC are given in Figure 15.

The testing parameters used in the example are in PHPTUV as follows:

- **Trip pulse time** =250ms
- **Trip output mode** = Non-latched



Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
TRPPTRC1: 1					
Master Trip(1)					
Operation		on			
✓ Trip pulse time		250	ms	20	60000
Trip output mode		Non-latched			

Figure 15. Parameters used for testing TRPPTRC

4.3 Testing Using OMICRON CMC 256plus and Test Universe

The OMICRON CMC 256plus is a highly precise relay tester and used as calibrator, widely used for testing protection relays, energy meters, and power quality analyzers. Omicron is ideal for applications requiring very high accuracy and high current. With Omicron, test to all generations of protection devices, including electromechanical, static and numerical can be done. Omicron also supports testing in IEC 61850 environments with GOOSE simulation and Sampled Values. (Omicron 2025)

Test Universe is OMICRON's comprehensive testing software suite designed for the CMC device family. It offers a range of application-optimized test modules for flexible and fully automated tests. In these test state sequencer and ramping functions were used for testing.

The relays output signals were connected to Omicron for the measurement of operating times, as given in Figure 16 and Figure 17. Also, relays were powered using the AUX output of Omicron.

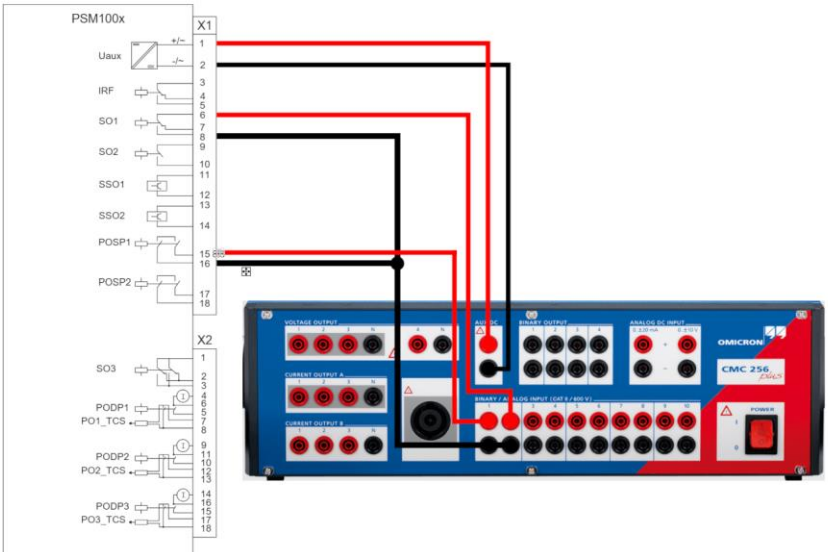


Figure 16. REX640 PSM outputs connected to Omicron inputs and auxiliary power

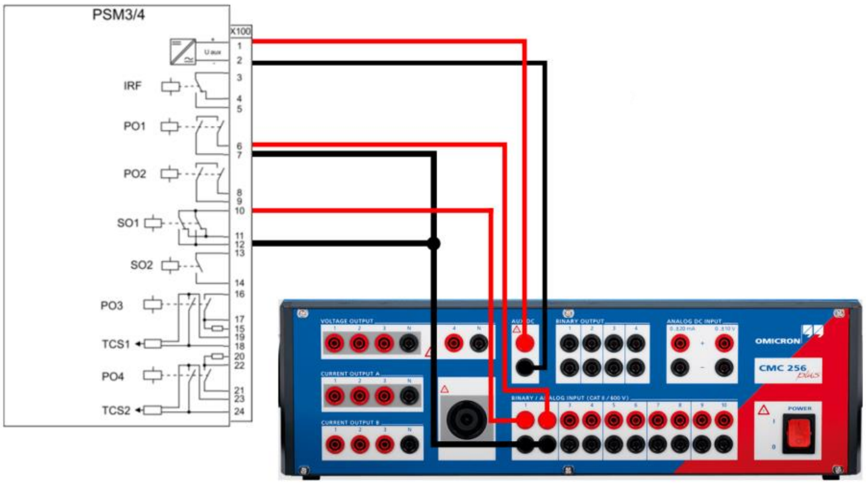


Figure 17. REX615 PSM outputs connected to Omicron inputs and auxiliary power

Frequency protection function testing was made by injecting phase voltages into the relay. The voltage output of Omicron was connected to voltage input channels, as given in Figure 18 and Figure 19.

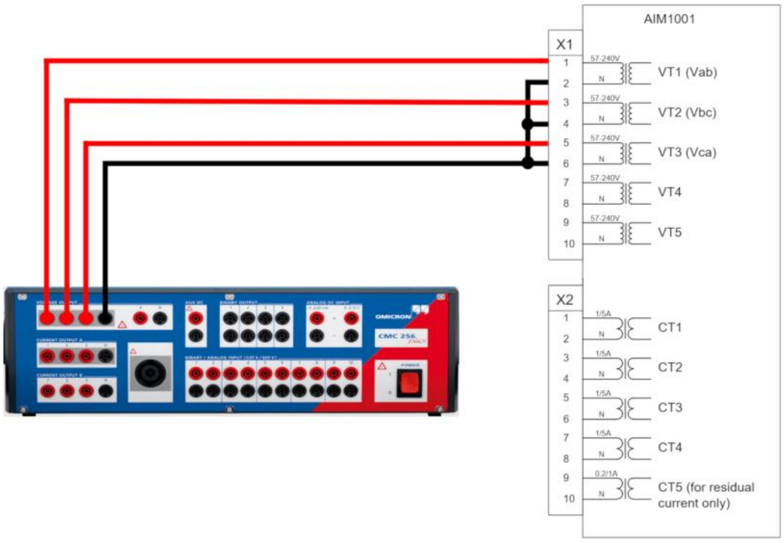


Figure 18. REX640 AIM connections to the relay for voltage measurement

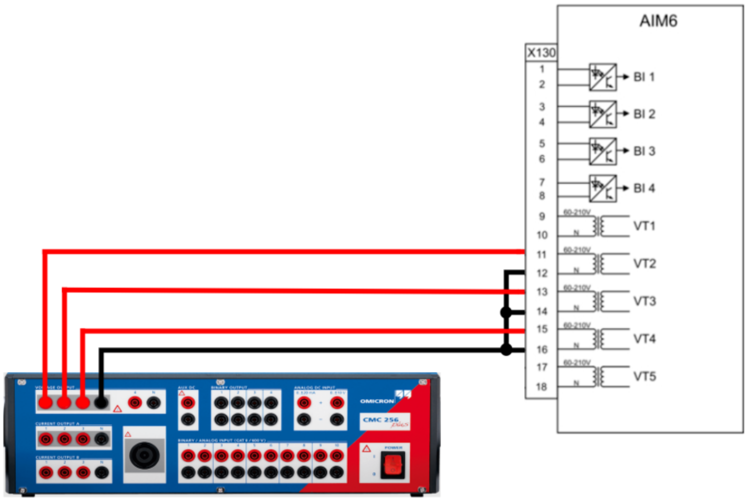


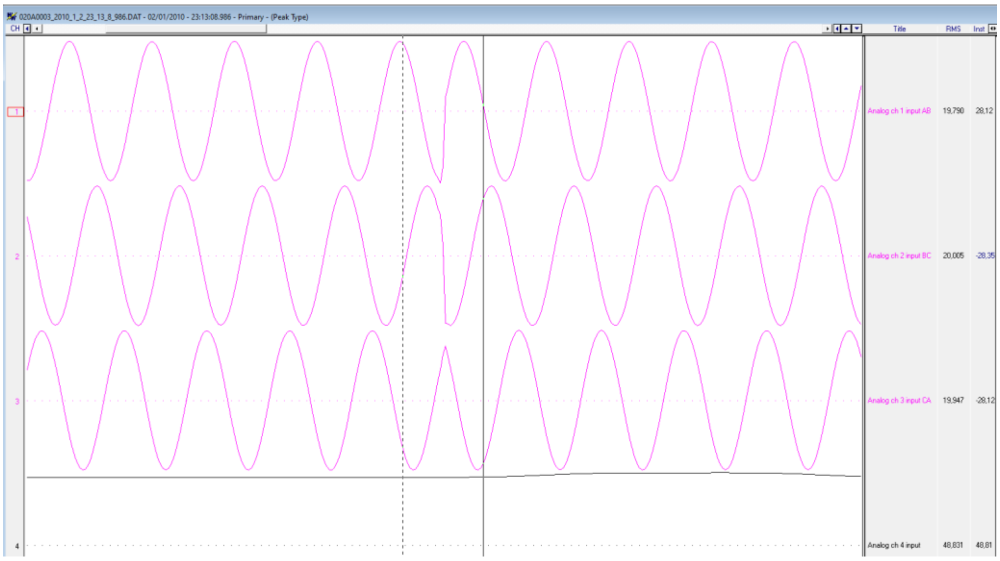
Figure 19. REX615 AIM connections to the relay for voltage measurement

5 TESTING UNDERFREQUENCY FUNCTION

5.1 Testing Protection Using Omicron 256plus with CMControl P Control Module

The first tests were carried out using CMControl P, which is the control option for Omicron 256plus, instead of using test universe (see Figure 20). This control option is often used for quick testing in laboratories and on-site. During testing, it was found that protection trip times were way longer than expected. After analyzing the disturbance records from the protection relay, it was found that injected signal was not continuous, as seen in Figure 21. In continuous on the injected signal caused delays in protection due to phase calculation reset. The tests were carried out with a step change of 1Hz, 0.5Hz and 0.1 Hz. For this reason, this test method using CMControl P control module is not possible to use in this type of testing.

Figure 20. Omicron 256plus with CMControl P front panel control (Omicron 2025)


020A0003_2010_1_2_23_13_8_986.DAT - 02/01/2010 - 23:13:08.986 - Primary - (Peak Type)

Title	RMS	Inst
Analog ch 1 input AB	19,790	28,12
Analog ch 2 input BC	20,005	-28,35
Analog ch 3 input CA	19,947	-28,12
Analog ch 4 input	48,831	48,81

Figure 21. In continuous on injected signal was seen on disturbance record

5.2 Testing Protection Using Omicron 256plus with Test Universe

5.2.1 Testing Large Frequency Change

The testing of frequency protection was done according to the FINGRID guidance. The testing was done with Omicron using the Omicron state sequencer software shown in Figure 22. The start and trip signal of the relay were connected to Omicron’s binary input channels. The operating times were measured using Omicron shown in Table 2. The operation in a large frequency change was tested with a step change from 50Hz → 48,75 Hz.

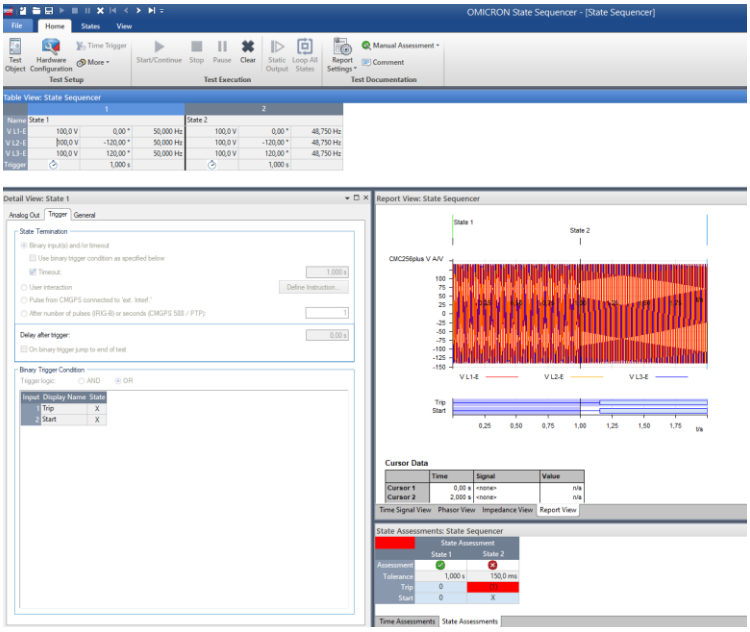


Table View: State Sequencer

	1			2		
Name	State 1			State 2		
V L1-E	100,0 V	0,00 °	50,000 Hz	100,0 V	0,00 °	48,750 Hz
V L2-E	100,0 V	-120,00 °	50,000 Hz	100,0 V	-120,00 °	48,750 Hz
V L3-E	100,0 V	120,00 °	50,000 Hz	100,0 V	120,00 °	48,750 Hz
Trigger		1,000 s			1,000 s	

Detail View: State 1

Analog Out | Trigger | General

State Termination

● Binary input(s) and/or timeout

☐ Use binary trigger condition as specified below

☑ Timeout: 1,000 s

○ User interaction — Define Instruction...

○ Pulse from CMGPS connected to 'ext. Interf.'

○ After number of pulses (IRIG-B) or seconds (CMGPS 588 / PTP): 1

Delay after trigger: 0,00 s

☐ On binary trigger jump to end of test

Binary Trigger Condition

Trigger logic: ○ AND ● OR

Input	Display Name	State
1	Trip	X
2	Start	X

Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	2,000 s	<none>	n/a

State Assessments: State Sequencer

🟥	State Assessment	
	State 1	State 2
Assessment	✓	☒
Tolerance	1,000 s	150,0 ms
Trip	0	(1)
Start	0	X

Figure 22. Omicron state sequencer window

Table 2. Test results for large frequency chance 50Hz to 48,75Hz

Test	REX640 Trip time (ms)	REX615 Trip time (ms)
1	157	158
2	157	157
3	157	157
4	159	154
5	159	158
6	159	158
7	157	158
8	158	159
9	157	155
10	157	155

The calculated mean time for the REX640 tests was 157,7ms, the median time was 157ms and the mode 157ms. The standard deviation of all tests was 0,95ms. The operating time of the circuit breaker is assumed to be 40ms. This means that the total operating time will be over in 195ms. Achieving valid test results for a total maximum protection time of 150ms, including relay and breaker operating times is impossible using this type of testing due to large frequency change. The disturbance record from one of the tests is shown in Figure 23 and settings and results from Omicron state sequencer in Figure 24 and Figure 25.

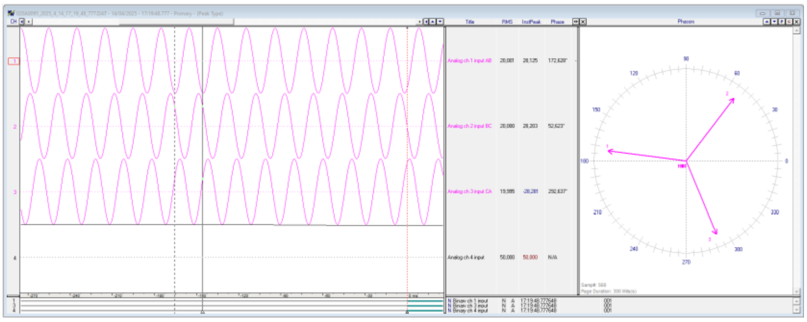
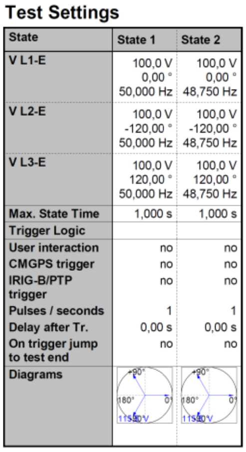


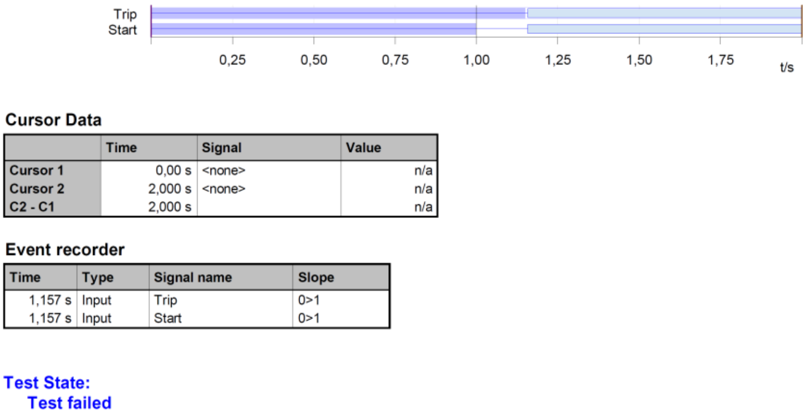
Figure 23. Disturbance record from relay



Test Settings

State	State 1	State 2
V L1-E	100,0 V 0,00 ° 50,000 Hz	100,0 V 0,00 ° 48,750 Hz
V L2-E	100,0 V -120,00 ° 50,000 Hz	100,0 V -120,00 ° 48,750 Hz
V L3-E	100,0 V 120,00 ° 50,000 Hz	100,0 V 120,00 ° 48,750 Hz
Max. State Time	1,000 s	1,000 s
Trigger Logic		
User interaction	no	no
CMGPS trigger	no	no
IRIG-B/PTP trigger	no	no
Pulses / seconds	1	1
Delay after Tr.	0,00 s	0,00 s
On trigger jump to test end	no	no
Diagrams		

Figure 24. Omicron state sequencer states for testing large frequency chance



Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	2,000 s	<none>	n/a
C2 - C1	2,000 s		n/a

Event recorder

Time	Type	Signal name	Slope
1,157 s	Input	Trip	0>1
1,157 s	Input	Start	0>1

Test State:
Test failed

Figure 25. Omicron state sequencer results for large frequency chance

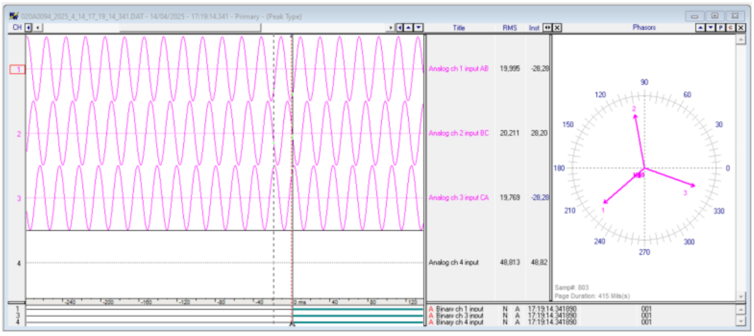
5.2.2 Testing the Operation of a Slow Frequency Change

The testing of frequency protection was done according to the FINGRID guidance. The testing was done with Omicron using the Omicron state sequencer software seen in Table 3. The start and trip signal of the relay were connected to Omicron's binary input channels. The operating times were measured using Omicron. The operation in a slow frequency change is tested with a step change of 0.1 Hz: 48,85 Hz → 48,75Hz

Table 3. Test results for slow frequency chance 48,85Hz to 48,75Hz

Test	REX640 Trip time (ms)	REX615 Trip time (ms)
1	75	93
2	78	92
3	75	91
4	79	93
5	77	91
6	77	93
7	75	93
8	79	95
9	77	92
10	75	94

The calculated mean time for REX615 tests was 92,7ms, the median time was 93ms and the mode 93ms. The standard deviation of all tests was 1,25ms. The operating time of the circuit breaker is assumed to be 40ms. This means that the total operating time will be under 140ms when 80ms operating time is in use. Achieving valid test results for total maximum protection time of 150ms, including relay and breaker operating times is possible using this type of testing. The disturbance record from one of the tests in Figure 26 and settings and results from the Omicron state sequencer in Figure 27 and Figure 28.

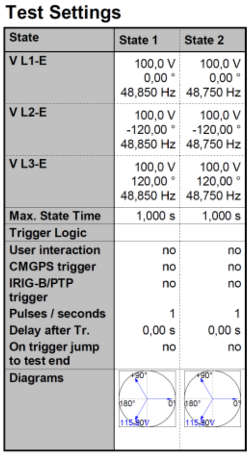

020A0094_2025_4_14_17_19_14_341.DAT - 14/04/2025 - 17:19:14.341 - Primary - (Peak Type)

Title	RMS	Inst
Analog ch 1 input AB	19,995	-28,28
Analog ch 2 input BC	20,211	28,20
Analog ch 3 input CA	19,769	-28,28
Analog ch 4 input	48,813	48,82

Samp#: 803
Page Duration: 415 Mils(s)

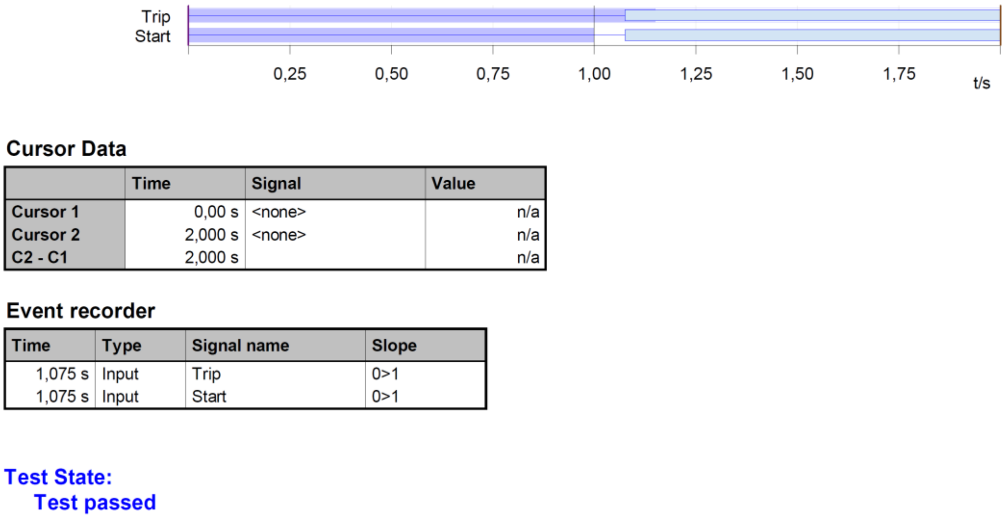
A Binary ch 1 input	N	A	17:19:14.341890	001
A Binary ch 3 input	N	A	17:19:14.341890	001
A Binary ch 4 input	N	A	17:19:14.341890	001

Figure 26. Disturbance record from relay


Test Settings

State	State 1	State 2
V L1-E	100,0 V 0,00 ° 48,850 Hz	100,0 V 0,00 ° 48,750 Hz
V L2-E	100,0 V -120,00 ° 48,850 Hz	100,0 V -120,00 ° 48,750 Hz
V L3-E	100,0 V 120,00 ° 48,850 Hz	100,0 V 120,00 ° 48,750 Hz
Max. State Time	1,000 s	1,000 s
Trigger Logic		
User interaction	no	no
CMGPS trigger	no	no
IRIG-B/PTP trigger	no	no
Pulses / seconds	1	1
Delay after Tr.	0,00 s	0,00 s
On trigger jump to test end	no	no
Diagrams		

Figure 27. Omicron state sequencer states slow frequency chance



Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	2,000 s	<none>	n/a
C2 - C1	2,000 s		n/a

Event recorder

Time	Type	Signal name	Slope
1,075 s	Input	Trip	0>1
1,075 s	Input	Start	0>1

Test State:
Test passed

Figure 28. Omicron state sequencer results for slow frequency chance

5.2.3 Test to Find Frequency Step Without Reset of Protection

The relay frequency function was tested with various frequency steps to determine the point at which the protection function did not reset due frequency step (see Table 4). The operating time was set to 80ms. When the frequency step was 0.3Hz or higher, the average operating time was around 150-160ms. A step from 0.25Hz and lower decreasing of operating times were seen and values 0.1 Hz or under operating times were near set value, as seen in Figure 29.

Table 4. Test results for different frequency steps

Start (Hz)	To (Hz)	Difference (Hz)	REX640 Operating time avg of 5 (ms)	REX615 Operating time avg of 5 (ms)
50	48,75	1,25	157	158
49,95	48,75	1,2	157	157
49,85	48,75	1,1	158	154
49,75	48,75	1	156	156
49,65	48,75	0,9	156	156

49,55	48,75	0,8	156	154
49,45	48,75	0,7	155	153
49,35	48,75	0,6	154	154
49,25	48,75	0,5	154	152
49,15	48,75	0,4	154	153
49,05	48,75	0,3	152	151
49,00	48,75	0,25	122	151
48,95	48,75	0,2	94	109
48,90	48,75	0,15	89	101
48,85	48,75	0,10	75	94

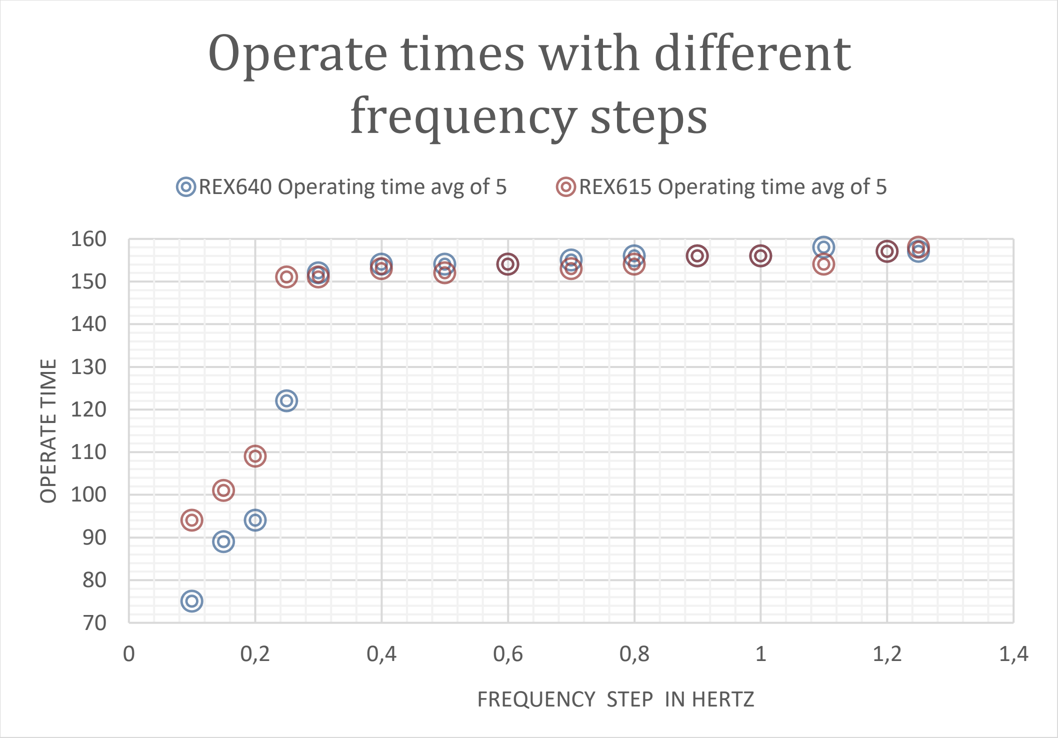
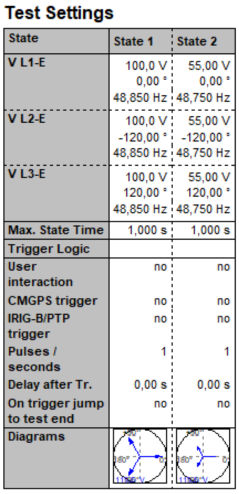


Figure 29. Test result of different frequency steps

5.2.4 Testing Blocking of Protection in Undervoltage Conditions

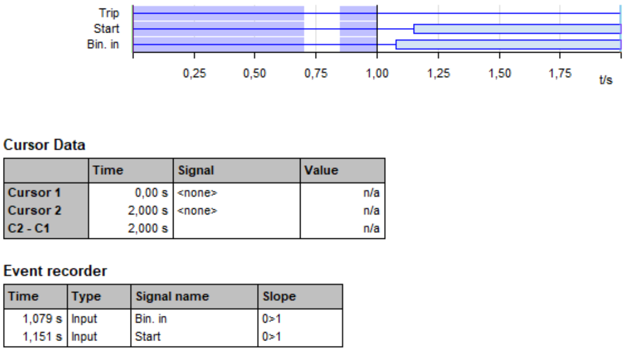
Undervoltage protection PHPTUV was set to the 0.6Un of nominal voltage. The start signal from the PHPTUV function block was connected to the block signal of the FRPFRQ frequency protection function. The block signal from PHPTUV and VMMXU three-phase voltage measurement function block was connected to the Omicron binary input. Also, the VMMXU three-phase voltage measurement function was used to set 0.1Un as the low limit for frequency protection. Voltages over and under 0.6x nominal were injected to the relay and the frequency was chanced in 0.1Hz steps. The setup and result from the Omicron state sequencer are shown in Figure 30 and Figure 31.



Test Settings

State	State 1	State 2
V L1-E	100,0 V 0,00 ° 48,850 Hz	55,00 V 0,00 ° 48,750 Hz
V L2-E	100,0 V -120,00 ° 48,850 Hz	55,00 V -120,00 ° 48,750 Hz
V L3-E	100,0 V 120,00 ° 48,850 Hz	55,00 V 120,00 ° 48,750 Hz
Max. State Time	1,000 s	1,000 s
Trigger Logic		
User interaction	no	no
CMGPS trigger	no	no
IRIG-B/PTP trigger	no	no
Pulses / seconds	1	1
Delay after Tr.	0,00 s	0,00 s
On trigger jump to test end	no	no
Diagrams		

Figure 30. Omicron state sequencer states for testing undervoltage conditions



Cursor Data

	Time	Signal	Value
Cursor 1	0,00 s	<none>	n/a
Cursor 2	2,000 s	<none>	n/a
C2 - C1	2,000 s		n/a

Event recorder

Time	Type	Signal name	Slope
1,079 s	Input	Bin. in	0>1
1,151 s	Input	Start	0>1

Figure 31. Results of testing undervoltage conditions

During the testing, it was discovered that when injected voltage levels were under the set undervoltage protection level 0.6Un of nominal frequency, the protection trip signal remains unactive. This prevents unwanted trips due to undervoltage situations

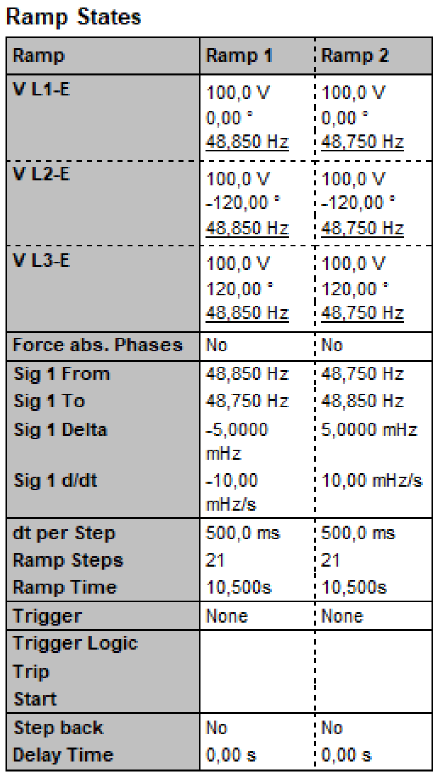
5.2.5 Verifying Activation and Recovery Frequency of the Protection Function

To verify the activation and recovery frequency, the ramping test module from the Omicron test universe was used. The ramping module is primarily designed to determine threshold values, such as pick-up and drop-off values. Different ramps for current and voltage can be created. For this testing, a frequency ramp was used.

The start value used for frequency protection was 48.80Hz. The ramp for activation starts from 48,85Hz and goes down to 48,75Hz The change of ramp value per step was -5mHz and time between two ramps steps was 500ms. The ramp for recovery was from 48,75Hz to 48,85Hz with similar steps as in activation. A total of five measurements were made. The results can be seen in Table 5. The setup and result from the Omicron ramping test are displayed in Figure 32, Figure 33 and Figure 34.

Table 5. Test results for activation and recovery

REX640	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Average**
Pick-up	48,795	48,795	48,795	48,795	48,795	48,795
Drop-off	48,815	48,815	48,810	48,815	48,815	48,814
REX615	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Average**
Pick-up	48,795	48,795	48,795	48,795	48,795	48,795
Drop-off	48,815	48,81	48,81	48,815	48,815	48,813



Ramp States

Ramp	Ramp 1	Ramp 2
V L1-E	100,0 V 0,00 ° 48,850 Hz	100,0 V 0,00 ° 48,750 Hz
V L2-E	100,0 V -120,00 ° 48,850 Hz	100,0 V -120,00 ° 48,750 Hz
V L3-E	100,0 V 120,00 ° 48,850 Hz	100,0 V 120,00 ° 48,750 Hz
Force abs. Phases	No	No
Sig 1 From	48,850 Hz	48,750 Hz
Sig 1 To	48,750 Hz	48,850 Hz
Sig 1 Delta	-5,0000 mHz	5,0000 mHz
Sig 1 d/dt	-10,00 mHz/s	10,00 mHz/s
dt per Step	500,0 ms	500,0 ms
Ramp Steps	21	21
Ramp Time	10,500s	10,500s
Trigger	None	None
Trigger Logic		
Trip		
Start		
Step back	No	No
Delay Time	0,00 s	0,00 s

Figure 32. Omicron ramping setting for testing activation and recovery

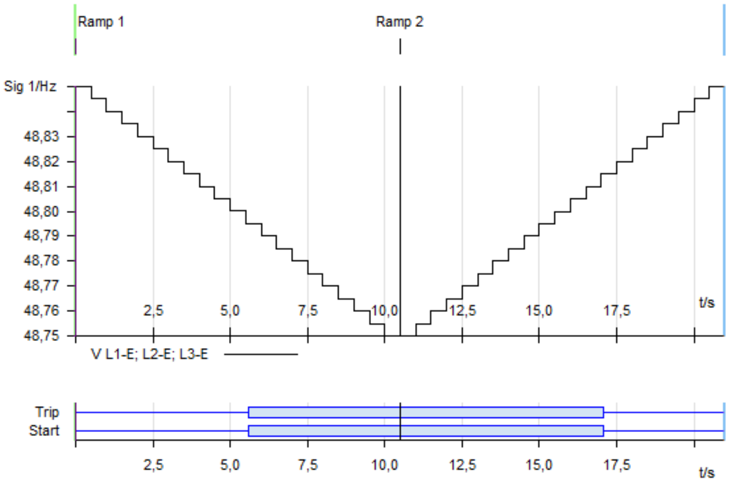
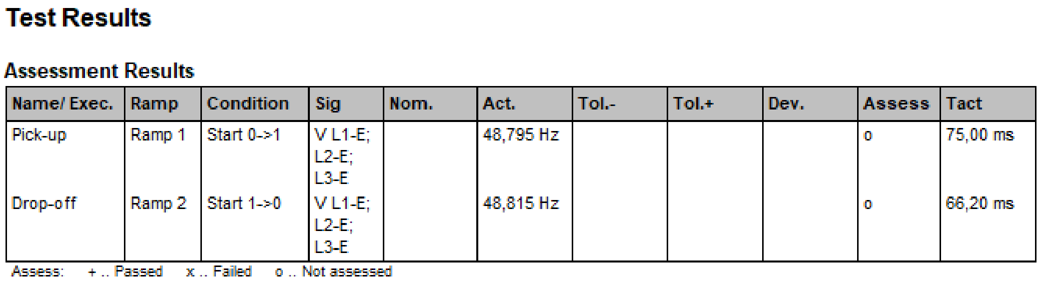


Figure 33. Test Ramp including trip and start signals



Test Results

Assessment Results

Name/ Exec.	Ramp	Condition	Sig	Nom.	Act.	Tol.-	Tol.+	Dev.	Assess	Tact
Pick-up	Ramp 1	Start 0->1	V L1-E; L2-E; L3-E		48,795 Hz				o	75,00 ms
Drop-off	Ramp 2	Start 1->0	V L1-E; L2-E; L3-E		48,815 Hz				o	66,20 ms

Assess: + .. Passed x .. Failed o .. Not assessed

Figure 34. Test results

The testing showed that the frequency protection activation and recovery time was reproducible when performed with small frequency steps. This approach ensured consistency in the test results. The typical activation time for protection was 75ms, which is slightly below the set operating time of 80ms. The reset delay was set to 0ms. During the testing, it was discovered that the recovery time is approximately three sine wave cycles, or 60ms. This is due to the type of frequency protection calculation of the relay, which requires three sine waves for accurate frequency determination.

6 VERIFYING SECONDARY TESTING TO COMPLY WITH FINGRID GUIDELINES

In this chapter, we will go through the results from the secondary testing. First, we will go through how results meet the requirements of Fingrid network code guidelines. Next, we will evaluate the possibility of making a technical note for the secondary testing of protection function for 150ms total operation time. The operating time of the relay should be under 110ms because in the Fingrid guidelines, a 40ms operating time for the circuit breaker is assumed. The operating time was tested with two different step frequency changes.

6.1 Large Frequency Change

The operation in a large frequency change was tested with a step change from nominal frequency → relay trip frequency - 0.05 Hz. The setting was 48.80 Hz and therefore, the change was from 50.00 Hz to 48.75 Hz. During the secondary testing, it was discovered that the typical operation time was longer than 80ms (see Table 2). This was due to the reset of protection function due frequency step. The average of delayed operating times were 157ms. For frequency protection three sine wave cycles are needed to determine frequency. Three sine wave cycles take 60ms at 50Hz, this shows that a reset in protection function has occurred during the frequency chance. No significant difference was observed between the relays. Due to the reset of protection function, this test will be treated as failed.

6.2 Slow Frequency Chance

The operation in a slow frequency change was tested with a step change of 0.1 Hz. The relay trip frequency + 0.05 Hz → relay trip frequency - 0.05 Hz. The setting was 48.80 Hz and therefore, the change was from

48.85 Hz to 48.75 Hz. The secondary testing revealed that the typical operation time was around 77ms for REX640 and for REX615 93ms (see Table 3). In the Fingrid guidelines, a 40ms operating time is determined for the circuit breaker. When the operating time from the relay and circuit breaker are added up , the total protection time will be less than 150ms. The test results show that the relays can be tested to comply with the Fingrid guidelines.

6.3 Activation and Recovery Frequency

Activation and recovery frequencies were measured using the ramping test. The start value used for frequency protection was 48.80Hz. The ramp for activation starts from 48,85Hz and goes down to 48,75Hz. The change of ramp value per step was -5mHz and time between two ramps steps was 500ms. The ramp for recovery was from 48,75Hz to 48,85Hz with similar steps as in activation. The testing showed that the frequency protection activation and recovery frequencies were in range of 0.05-0.15Hz during the testing. The testing showed that the frequency protection activation and recovery time was reproducible when performed with small frequency steps. This approach ensured consistency in the test results. For this test there are no limits in the Fingrid guidelines. Due to the accuracy of the relay, this test can be tested to comply with the Fingrid guidelines.

6.4 Correct Operation in Undervoltage Conditions

Undervoltage blocking was implemented to prevent unwanted frequency protection operation in voltage drops. Secondary testing was done by injecting voltage levels under the set undervoltage protection level 0.6Un. During the undervoltage frequency protection, the trip signal remained inactive. This prevents unwanted trips due to undervoltage situations. This test complies with the Fingrid guidelines.

6.5 Zero Voltage Lockout

VMMXU three-phase voltage measurement function was used to set the low limit for frequency protection. Protection was tested against unwanted frequency protection operation in a total power loss. During the testing, undervoltage frequency protection trip signal remained inactive. This prevents unwanted trips when no voltages are present. This test complies with the Fingrid guidelines.

7 CONCLUSIONS

The focus of the thesis was on secondary testing for fast frequency protection function. The need for fast operation times comes from Network codes around Europe. The required protection times are hard to achieve due the nature of frequency protection calculations. In this thesis it was discovered that the requested protection time can be achieved when the frequency change is under 0.66Hz/s. This does not cover the worst case scenarios seen on distribution networks. It seems that the current technology does not guarantee the correct operation of protection equipment in the presence of this kind of disturbance. Due to the fact that it is not possible to achieve protection times required in the Fingrid network code, technical notes will not be written.

Larger studies outside of the scope of this thesis would be to analyze the required total operating time. Now the European Network of Transmission System Operators for electricity has a recommendation of total protection time 200ms including the breaker delay. This is 50ms longer than the time required in the Fingrid network code. With two different operating times, depending on frequency drop level, it may be possible to achieve the required protection times.

The decrease of system inertia due to the decommissioning of generation units with rotating masses will make frequency protection more important for network stability. This means that new ways to measure the frequency should be studied and implemented to use.

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