Resonant Test Systems With Variable Frequency for On-site Testing and Diagnostics of Cables

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Abstract:

Frequency-tuned resonant test systems are, meanwhile, state of the art for on-site testing and diagnostics of high-voltage extruded cables. After experience with some realised systems the technical data, especially the weight-to-power ratio , and the performance have been further optimised. A specially adapted diagnostic technique has been developed for this application. Basic research on cable samples with different failures has qualified AC voltage near to the power frequency to be the optimum test voltage wave shape. Resulting from these it is logical to apply this test voltage shape also on medium-voltage cable systems. An example is introduced in this paper.

1. Introduction and history

Frequency-tuned resonant test systems were introduced at the end of the seventies for GIS on-site testing /1/ and later on also applied for after-laying tests of high-voltage (HV) cables /2/. These test systems consist mainly of a frequency converter, an exciter transformer and a resonant reactor with fixed inductance. Resonant reactors with fixed inductance were designed in the beginning as cylindrical modules in an insulating case.

Because of the limited heat dissipation through the insulating tube this early cylinder-type design enables test currents of some Amps in a short-time duty cycle only, which may be sufficient for testing short cables of a few hundred meters. The testing of HV cables of typical lengths between 4 and 15km requires test currents between 100 and 200A.

First steps to meet this test current requirement were done with two powerful frequency-tuned resonant test systems in the beginning of the nineties, using larger cylinder-type resonant reactors, see systems no. 1 /3/ and 2 /4/ in table 1. A remarkable short-time power has been be reached.

Another important step was the introduction of a test system with a first tank-type reactor (no. 3 /5/). The heat dissipation through the metallic vessel which can be optimally enforced by external radiators with fans is much better and allows long-time tests, for instance 8 hrs. Other essential advantages are the better resistance against mechanical shocks and the option of a cable plug-in connection to lead the test voltage to the cable to be tested, see also chapter 2.2. . Meanwhile this design has proven to be optimum, the systems 5 - 14 are realised in this way. An exception is the system no. 4 using a cylinder-type resonant reactor /6/. The remarkable test power of limited duty cycle can be reached by an external heat exchanger.

2. Progress in the design of frequency-tuned resonant test systems

After frequency-tuned resonant test systems have been recognised to be the most effective and only practicable solution for the cable on-site testing of HV cables, there was an uncertainty to define a test frequency range larger than that of power frequency for

No.	Year	Origin	Rated voltage	Rated current	Test power (related to 50 Hz)	Frequency range	Weight-to-power ratio of the system
1	1992	Switzerland	250 kV	37 A	23 MVA	20 - 160 Hz	unknown
2	1993	South Africa	132 kV	122 A	16 MVA	50 - 100 Hz	unknown
3	1996	Germany	160 kV	40 A	8 MVA	35 - 71 Hz	1.9 kg/kVA
4	1996	Switzerland	220/440[1)] kV	66/133[2)] A	24/48 MVA	30 - 300 Hz	0.9 kg/kVA[3)]
5 + 6	1998	Germany	150/300[4)] kV	90/180[5)] A	22.3/44.3 MVA	30 - 300 Hz	0.97 kg/kVA
7 + 8	1998	Germany	254/400[4) 6)] kV	80/160[5)] A	31.4/62.8 MVA	25 - 300 Hz	0.8 kg/kVA
9	1998	Germany	160/320[1)] kV	50/100[2)] A	26.5 MVA	30 - 200 Hz	1.1 kg/kVA
10	1999	Germany	230 kV	83 A	34 MVA	25 - 300 Hz	0.8 kg/kVA
11	2000	Germany	160/320[1)] kV	50/100[2)] A	26.5 MVA	30 - 300 Hz	1.1 kg/kVA
12	2000	Germany	220 kV	78/156[2)] A	32/64 MVA	25 - 300 Hz	0.85 kg/kVA
13	2000	Germany	230 kV	83 A	34 MVA	20 - 300 Hz	0.8 kg/kVA
14	2000	Germany	160/320[1)] kV	50/100[2)] A	26.5 MVA	30 - 300 Hz	1.1 kg/kVA

[1)] 2 reactors in series; [2)] 2 reactors in parallel, [3)] specific reactor weight only;
[4)] 2 systems in series; [5)] 2 systems in parallel, [6)] 504kV for GIL testing

Table 1: Survey of realised systems for HV cable on-site testing.

laboratory testing, which is defined to be within 45 and 65 Hz /7/.
The permissible frequency range (f_{min} - f_{max}) determines the obtainable load capacitance range (C_{min} - C_{max}) /8/:

$$(f_{max} / f_{min})^2 = C_{max} / C_{min} \qquad (1)$$

With f_{min}=45 Hz and f_{max}=65 Hz the load range, i.e. the ratio C_{max}/C_{min} is approx. 2, which is not sufficient to design a practicable frequency-tuned resonant test system. An extended frequency range is absolutely necessary. So there were more or less cautious approaches for the frequency range in the beginning, see systems no. 1, 2, 3 in table 1. An essential step was done by the CIGRE WG 21.09 /9/ defining for cable on-site tests a frequency range from 30 to 300 Hz to be “near to power frequency”. All following realised systems were based on this recommendation, see systems no. 4 - 14 in table 1. Basic investigations on the breakdown behaviour of polyethylene samples with typical failure pattern have confirmed that there is no significant difference in the breakdown behaviour over a wide frequency range /10/.

2.1. Frequency range and quality factor

With respect to a maximum test power and a lowest weight-to-power ratio (kg/kVA) the frequency range is the essential for the design of a frequency-tuned resonant test system. The lower the minimum permitted frequency $f_{min,}$ the lower is the necessary test power P to test a given capacitance C with a given test voltage V:

$$P = 2 \pi f_{min} \cdot C \cdot V^2 \qquad (2)$$

But for the weight-to-power ratio this tendency is practically limited by a larger cross section of the iron circuits of the resonant reactor and of the exciter transformer, which is required to avoid the saturation of the iron core at lower frequencies. The enlargement of the magnetic circuit leads to an essential higher weight. So the weight-to-power ratio of the system, i.e. the weight of the system related to the 50-Hz-equivalent test power given in kg/kVA, would go up. Table 1 contains as far as known the weight-to-power ratio of the realised systems. It is obvious that the weight-to-power ratio came down after choosing 30 Hz as a minimum frequency. The optimum for the minimum frequency regarding to a minimum weight-to-power ratio is even below 30Hz, see the systems no. 7, 8, 10 and 12, having a minimum frequency of 25 Hz or even 20 Hz, no. 13 and a lowest weight-to-power ratio of 0.8 kg/kVA. Consequently a minimum frequency between 20 and 25 Hz is recommended.
The maximum test frequency f_{max} determines the load range as given in equation (1). A frequency range 30 – 300 Hz leads to a load range of the factor 100, which seems to be sufficient. With the increase of the frequency the frequency-depending supplementary losses (hysteresis losses, skin effect etc.) in the resonant reactor and exciter transformer decrease also. Besides these an increased

polarisation heat in the measuring capacitor has to be considered. From this point of view a higher frequency than 300 Hz is disadvantageous.

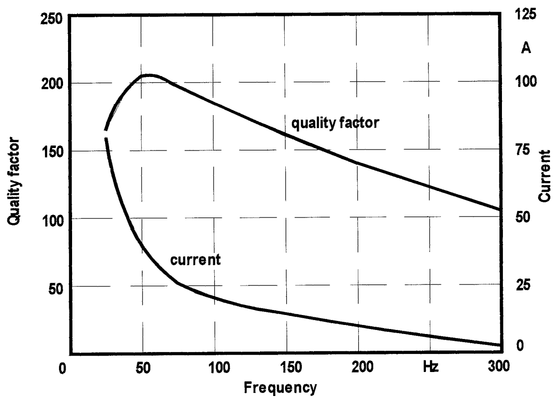

Fig. 1:Quality factor and current vs. frequency for a resonant test system 80A, 254kV, no. 7, 8 in table 1

The quality factor q of a resonant test system is the ratio between test power and required feeding power to cover all ohmic losses in the test circuit. Because the polyethylene insulation of an extruded cable has a very low power factor (tan δ, ca. $3 \cdot 10^{-4}$) the quality factor is determined by the resonant reactor and exciter transformer losses. A maximum quality factor would be desirable regarding a minimum feeding power, but it would require larger cross sections of the iron core and of the copper winding wire, which results in a higher weight-to-power ratio . For low frequencies (and therefore high currents) the quality factor is determined mainly by the pure ohmic losses in the copper wire, for higher frequencies by all frequency-depending supplementary losses. Both influences result in a maximum of the quality factor over frequency. As an example fig. 1 shows the quality factor and current versus frequency for the resonant test systems no. 7, 8 in table 1. The quality factor of ca. 160 is connected with the weight-to-power ratio of only 0.8kg/kVA.

Both effects, i.e. the lowering of the test power by a lower frequency and a sufficiently high quality factor, which is much higher than for resonant reactors with variable inductance, enable the generation of some 10 MVA test power with an on-site available feeding power of some 100 kVA.

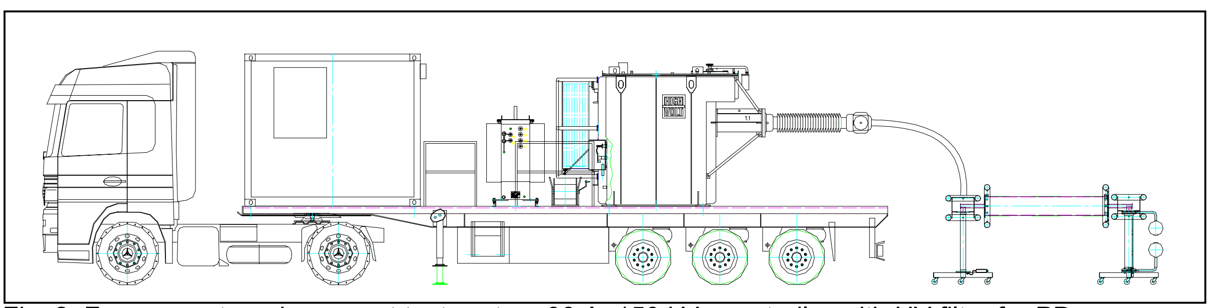

Fig. 2: Frequency-tuned resonant test system 90 A, 150 kV on a trailer with HV filter for PD measurement

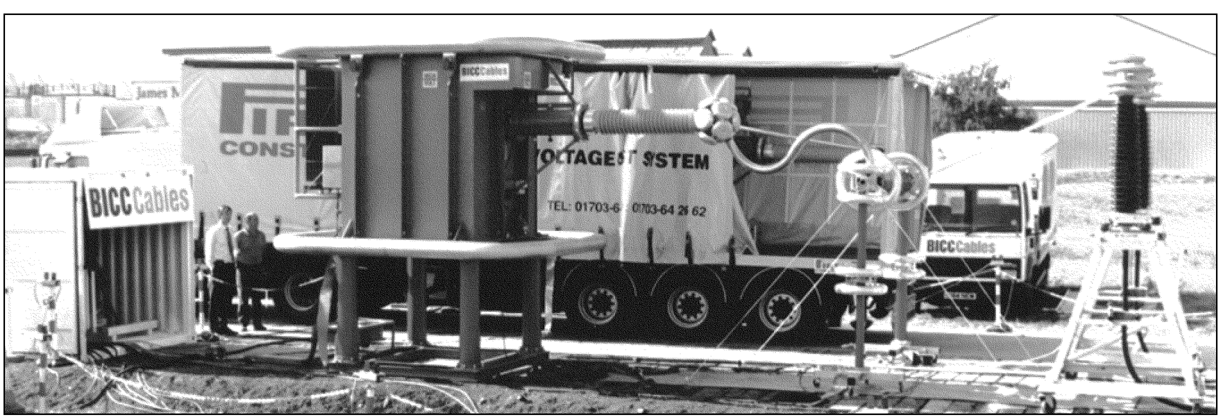

Fig. 3: Parallel connection of two identical test system 90A, 150kV to extend the available test current to 180A (By courtesy of BICC Cables Ltd., U.K. and Pirelli Construction Company Ltd., U.K.)

2.2. Connection technique and accessories

In practice it is sometimes impossible to bring the heavy test system to the immediate vicinity of the cable to be tested. So it is necessary to lead the test voltage over some 10 m. This can be done by a bar wire, which is supported by insulating posts. Thereby the entire transmission line must be surrounded by a safety loop with warning lamps and emergency-off switches. A more convenient solution is to use a connection cable with two flexible terminations at the ends - one is connected to the HV terminal of the resonant reactor and the other to the cable to be tested. Such cables are available as so-called “emergency cables” originally meant for provisional connections in substations. By means of this cable the test voltage can be lead easily into indoor substations or down to underground cable facilities.
Tank-type resonant reactors enable the direct plug-in connection of such a connection cable. Two solutions for this direct connection cable plug-in have been realised meanwhile:
- The plug-in connection can be made directly by an SF_6-immersed sealing end for transformers. The other end of the cable has a standard air cable termination or a sealing end for GIS acc. to IEC 60859, to be plugged in a GIS, which terminates the cable to be tested. In the latter case there is a closed encapsulation between the resonant reactor and the cable under test, which provides best preconditions to eliminate outer electromagnetic disturbances (noise) and to enable sensitive PD measurements.
- The resonant reactor is fitted with an oil-SF_6-bushing. The SF_6-part of this bushing projects into a cylindrical SF_6-vessel. A SF_6-air-bushing projects into the other end of the vessel (fig. 2). Both bushings are connected by a plug contact inside the vessel. The SF_6-air bushing can be replaced by a connection cable with a standardised sealing end as described above.

2.3. Transportation system

In spite modern cable on-site test systems have a lowest weight-to-power ratio the resulting total weight of such a system is about 30 tons.
Such systems can be handled by customary truck trailers being modified for this purpose. Fig. 2 shows a trailer for the transportation of test system no. 5 in tab. 1. The control and feeding unit, including the inverter is located in an air-conditioned and illuminated 10ft container at the front side of the trailer. This container serves for the operation of the system. It has a door, windows and a board mains. The resonant reactor is located above the trailer axles, its bushing projects to the rear side. The exciter transformer is standing between the container and the resonant reactor. A foldable stairs serves for the access to the trailer platform, which is surrounded by a safety railing. The trailer has a foldable roof and side canvas to protect the system against bad weather during transport and parking.
Alternatively, with reference to future ship transportation all control equipment and the exciter transformer can be arranged in a 20ft container. The resonant reactor is designed to fit on a so-called flat rack container, for its fixing it has counterparts for container twist locks at the bottom plate and for lifting container fittings at the top plate. By storing the accessories in the container the test system is split up into two units for sea transportation – the 20 ft container and the resonant reactor in a container flat rack.
Fig. 3 shows the parallel operation of a containerised and a test system on a trailer, to extend the load range, systems no. 5 and 6 in table 1.

2.4. Software for control and protocol

The control and feeding unit contains all power electronics and control modules required for operating a frequency-tuned resonant test system The entire system is controlled by a PLC, type SIMATIC S5-95U. An operator panel COROS OP 15 is used for the input of the test data and to display the measured values (voltage,. frequency, current) and other

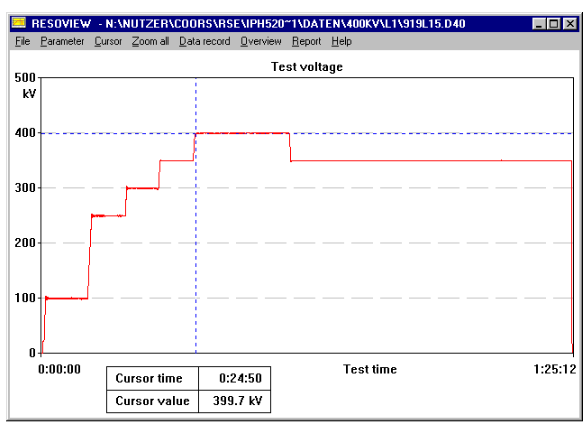

Fig. 4: Test record voltage vs. test time

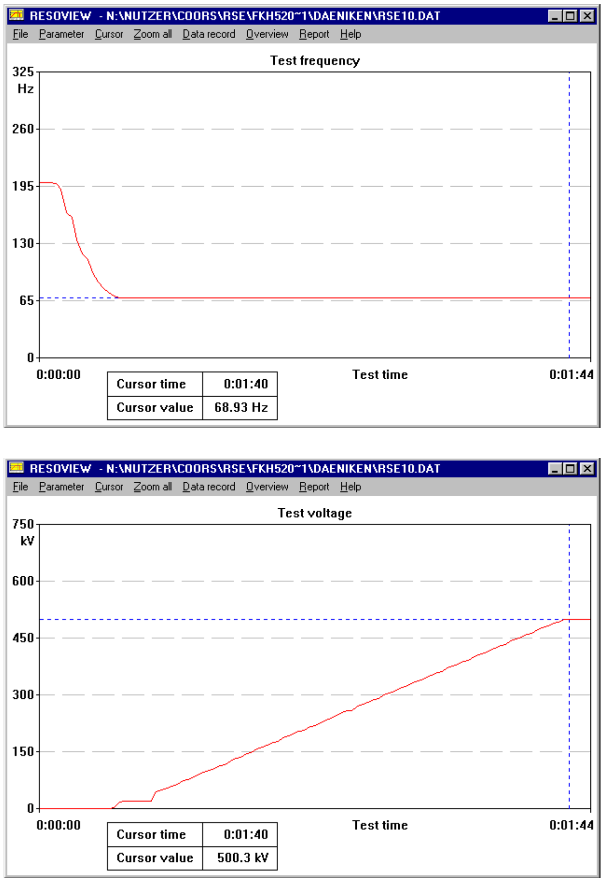

Fig. 5: Records for searching resonance frequency, (upper screen) and following voltage rise (lower screen)

necessary information concerning the state of the system.
For a remote control the SIMATIC unit can be linked to an external PC, preferably a laptop, via an RS 232 interface. The laptop enables by means of a special software a more comfortable operation of the system, because much more information can be shown on the screen than on the operator panel display. This software stores during a test every second all relevant data like test voltage, test current, frequency, inverter pulse width, resonant reactor temperature etc. on the hard disk. With the help of this data a record can be generated showing test voltage, resonant reactor temperature etc. versus test time, see fig. 4 with a real test cycle and fig. 5 showing the frequency searching with following voltage rise to the preselected test voltage level.

2.5. Diagnostics technique

Frequency-tuned resonant test systems can be prepared for PD measurements according to IEC 270. For the suppression of disturbances caused by the steep switching flanges of the inverter bridge the control and feeding unit generates a signal to trigger the gating unit of an especially modified PD detector /11/. Additionally HV filters consisting of measuring capacitor, blocking impedance and coupling capacitor can be applied for PD measurement purposes, see fig. 2 right side. A PD sensitivity below 10 pC can be reached. The obtainable PD sensitivity under on-site conditions depends on the environmental conditions (external noise, earthing conditions, etc.) and from the damping conditions and length of the cable. It is estimated that the IEC 270 method can be applied up to a cable length of max. 2.5 km, when the PD measurement is executed only from one end, and max. 5 km from both ends.
For longer cables the sensitivity of PD measurements according to IEC 270 becomes to low and non-conventional methods using sensors in the cable joints must be applied /12/. An encapsulated cable plug-in connection between resonant reactor and cable under test (as described in chapter 2.2. before) provides a totally screened circuit with optimal preconditions for sensitive PD measurements.

3. Frequency-tuned resonant test systems for medium-voltage cable testing

After frequency-tuned resonant test systems have been introduced successfully for the on-site testing of HV cables there is a certain logic to apply this principle also on the testing of medium-voltage cables, especially under the point of view to enable PD and power factor diagnostics. Before VLF (very-low-frequency) test systems for medium-voltage cables became applicable /13/, there was indeed the attempt to introduce a frequency-tuned resonant test system for this purpose /14/. But it was to weak in power to master water-tree-damaged and older oil-paper cables with their bad power factor.

3.1. Selection of technical data

There are some special aspects to select the technical data for future frequency-tuned systems for medium-voltage cables.
In opposite to the HV cables there is till now no recommendation related to the test level, i.e. the multitude of the phase-to-earth voltage U_0 for the different system voltages. At the other side the maximum length of the cable to be tested is not so clear. For the test system a

rated voltage of 36 kV meeting 3 U_0 of the 20 kV class and 2 U_0 of the 30 kV class and a rated current of 17 A representing a cable capacitance of 2.5 µF (ca. 10 km) at 30 Hz have been chosen. The triple 36 kV, 17A, 30 Hz results in a 50-Hz-equivalent power of 1MVA. Different to HV extruded cables a worse power factor has to be considered for medium-voltage cables, which will determine the quality factor of the resonant circuit now. So it makes no sense to design exciter transformer and resonant reactor for an extremely high quality factor. This is possible also, because a much lower feeding power related to HV cable test systems must be supplied.

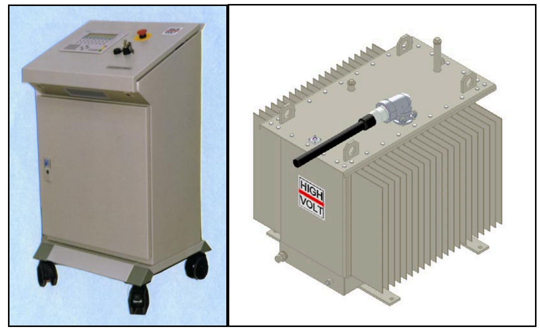

Fig. 6: Control and feeding unit and resonant reactor 17 A, 36 kV for testing cables up to 10 km

3.2. Design example

The frequency-tuned resonant test system for medium-voltage cable on-site testing consists of a control and feeding unit, an exciter transformer and a resonant reactor, see fig. 6. The resonant reactor is realised in a conventional power transformer design, i.e. oil-immersed in a metal tank. It contains besides the active part (coil and core) a capacitor for the voltage measurement. The test voltage is lead out via a plug-in connection and a 20 m-connection cable with a air cable termination at the other end. To adapt the output voltage of the control and feeding unit to the resonant circuit there is a dry-type exciter transformer. The control and feeding unit is desk type and contains all power electronic and control components including a peak voltmeter, see also chapter 2.4 before. The medium-voltage test system has the following technical data:

Nominal voltage:		36 kV
Nominal Current:		17 A
Frequency range:		30 - 300 Hz
Capacitance range:		25nF - 2.5 µF (ca.0.1-10km)
Duty cycle (at 20°C):		
for nominal current 17A:		30 min ON - 45 min OFF
for reduced current 11A:		continuously
Weights:	Resonant reactor	1100 kg
	Exciter transformer	295 kg
	Control and feeding unit	95 kg
	Total	1490 kg

4. Conclusions

Marked progress has been made in the design and performance of frequency-tuned resonant test systems for on-site testing and diagnostics of HV extruded cables:

- A frequency range beginning at 20 ... 25 Hz and ending at 300 Hz enables to reduce the weight-to-power ratio of such test systems to 0.8 kg/kVA or lower.
- A tank-type reactor with radiators is the optimum solution related to the permissible duty cycle and a plug-in connection technique to the cable under test.
- There are optimised solutions for the transportation of such a system based on containers and trailers.
- An adapted PD technique and comfortable PC software for control and protocol are available.

The application of frequency-tuned resonant test systems for the on-site testing of medium-voltage cables is a logic conclusion. An example has been introduced.

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