RESONANT POWER SUPPLY KIT SYSTEM FOR HIGH VOLTAGE TESTING

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Abstract. Test equipment of very low weight has been built which is frequency-tuned within a regulation range of one to two times power line frequency. It differs from all common series resonant testing installations as it makes use of rotating alternator modules for current injection into series-connected inductors and parallel-connected capacitors forming a kit system. The kit idea is illustrated by a couple of module designs which cover a range of voltage and power ratings that correspond to a series of testing transformers, these if feasible being more expensive in cost and weight,

- from 50 kV, 500 kVA,
  weight realized in smallest kit version
  600 kg, i.e. 1.2 kg/kVA.
- to 600 kV, 5 000 kVA,
  weight realized in highest normal kit voltage version
  4 000 kg, i.e. 0.8 kg/kVA.
- or to 200 kV, 20 000 kVA,
  weight realized in highest cable-test power extension
  8 000 kg, i.e. 0.4 kg/kVA.

The testing kit allows on-site testing of GIS-substations or other large-scale applications by standardized LC-coupling. As some actual examples show, important applications will be found, too, in the fields of cable testing and of transformer testing, both on site.

INTRODUCTION

During the past ten years a lot of field experience has been gained in using plain series resonance and frequency tuning, mostly on-site, after erection of GIS-substations [2,3]. As practical problems arose new reflections were initiated. So there followed an interactive sequence of performing tests, investigating the behaviour of the test material and designing new test equipment.

Former series-resonance approaches (fig.1) considered the fact that an appreciable reactive power P_r is required when testing an electrical insulation of a given capacitance C at an ac-test voltage V of frequency f. The power P_r as depending on test current I amounts to

$$P_r = V \times I = 2\pi f (C \times V^2)$$

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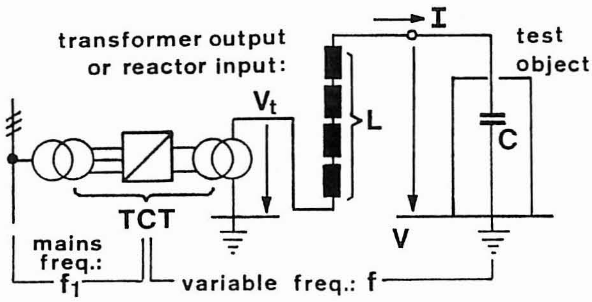

Fig. 1. First Frequency-Tuned Series Resonant Test Circuit.

TCT	Thyristor frequency converter with two transformers, square wave converter rated 50 kVA, 500 V, max. 300 Hz, output transformer rated 9 kV, min. 50 Hz.
L	Inductance of composite reactor 216 H.

and cannot be supplied by conventional testing transformers because of their poor mobility if V on site is very high, and because of lacking power if C and V are high. Therefore series resonance uses high Q-factors (low dissipation) of an inductive coil and of the series-connected load capacitance (which is not part of the equipment) so that a voltage amplification A can take place. With current injection at an input voltage V_t (current transformer output) the voltage amplification depends mainly on the inductance L of the coil and its resistance R, thus reaching A-values somewhat below the Q-factor of the coil (typically 100...150):

$$A = V / V_t < Q \leq 2\pi f \times L / R$$

Tuning to resonance $A \rightarrow Q$ must be made by variable L when taking the current injection from the mains (f_1 = 60 Hz). This implies very heavy structural means to set the air gap. Conclusive progress was not achieved until frequency tuning (fig. 1) has been introduced in 1980 [1], which resulted in bringing the specific weight of the total equipment from about 5 kg/kVA (variable L) or even 50 kg/kVA (testing transformer installation in a lab) down to approximately 1 kg/kVA. This low value has been reached with the weight of 3000 kg, the actual power output not exceeding 3000 kVA. However, the lowest specific weights cannot be realized if test objects are too small compared with the equipment. On the contrary, small capacitancies (typically 1...2 nF as encountered with extension or repair work in GIS-substations) bring about extremely high test frequencies even with four inductors in series. The application of such reactors of very high inductance for tuning only (300 Hz according to IEC standards) instead of supplying high power and high voltage, represents an unduely poor exploitation of the test material involved. Further, poor impedance adaptation by the invariable coupling transformer results in lacking power if high power is required (as for cable-testing). Finally, the square wave output of the frequency converter renders the equipment worthless for detection and measurement of partial discharges (PD).

The new concept is based on rotating ac generators for current injection allowing a reduced frequency regulation ratio of $f/f_1 = 2$ instead of 5 (f = 60...120 instead of 300 Hz with frequency converter). For this purpose a capacitor C_p has been added (fig.2), parallel to the test load in order to sustain resonance. It is worthy of note that such a resonant power supply is compatible with no-load testing conditions (as a transformer would be), and that a fundamental requirement for any PD-detecting procedure is fulfilled owing to the inherently noise-free voltage wave that rotating machines can generate. With a refining filter and an adequate wiring of the whole testing system, a sine wave will be produced being not only free from noise (harmonics of the order of 100 kHz), but also from all distortions (harmonics of the order of 1 kHz).

The wide application field of such a circuit led to the idea of a resonant power supply kit system. There are mainly three application branches which may constitute different lines of equipment, each with increasing ratings :

- Ordinary self-supporting series resonant circuits for large-scale testing operations including GIS-substations. Size of equipment depending on the test voltage (V).
- High power series-resonant circuits for testing rather long installed cable lines of typically 110 kV line voltage or more [4]. Size of equipment depending on the number of parallel-connected reactors (N).
- Feeding into an auto-excited transformer through the primary or secondary winding while adequate compensation must be provided either in a series or in a parallel coupling mode depending on power balance and on controllability (type of alternator). Size of equipment as required by the size of the transformer under test, the ratings of which range from an instrument transformer to a big power transformer (P).

FUNDAMENTALS OF RESONANCE

An ordinary circuit of self-supporting resonance (fig.2) may be considered as a quadripole of the transmission line type the reactive components of which (L, C_p) define its characteristic values with no load,

resonance frequency $f_0 = (2\pi \sqrt{L \times C_p})^{-1}$

and wave impedance $Z_0 = \sqrt{L / C_p} = V / I_L$.

Such a circuit affords, first of all, transformation of impedancies from input (current I_L) to output (voltage V) or reverse, the respective terminals of input (left side) or output (right side) requiring an external impedance of very low respectively of very high value ($V_t / I_L \rightarrow 0$, $V / I \rightarrow \infty$).

If the quadripole is excited by a tuned HV-source (transformer at right-hand terminal) an amplified current I_L appears at the short-circuited left side thus representing parallel resonance. For forward voltage amplification ($V / V_t = Q_0$) a tuned source of frequency f_0 is connected to the left terminal as shown in fig.2. This is plain series resonance. As an outcome of the impedance transformation law, a sharp transition of input impedance from high to low values takes place when

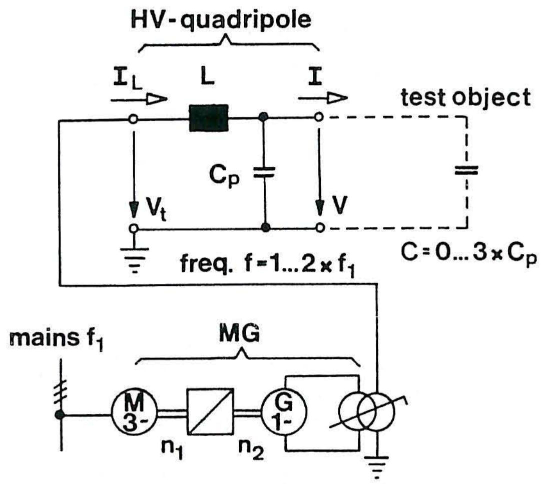

Fig. 2. Basic Kit LC-Circuit.

MG	Motor-generator set 10 kVA, 0.3 - 3.6 kV.
M3 ~	Three-phase induction motor, n_1 = 3600 rpm at f_1 = 60 Hz.
G1 ~	Two-pole single-phase synchronous alternator with variable shaft speed of transmission n_2 = max. 7500 rpm.

the frequency to be tuned approaches resonance ($f \rightarrow f_0$). In parallel resonance respectively, the output impedance (V/I) would sharply break down into short-circuit conditions out of resonance. This implies the need for a synchronous alternator to deliver the short-circuit current when feeding into a parallel resonance system (voltage may develop only in resonance).

If neither source nor load is connected to the output (C = 0 at open end), only the circulating current I_0 flows with a related reference power P_0:

$$I_0 = I_L(f_0) = V / Z_0 , \quad P_0 = V \times I_0 = V^2 / Z_0 .$$

If the test voltage is kept constant (V = const) the input voltage V_t (f_0) reaches a minimum value when the motor-generator drive (MG) approaches the speed of resonance. This no-load input matches the quality factor Q_0 of the equipment where the respective power-factors p_L , p_C characterize the dissipation of the coil and the capacitor, for instance in case of the implemented kit modules at an expected upper frequency limit of f_0 = 120 Hz:

$$p_L = R / Z_0 = (2\pi f_0 \times L / R)^{-1} \geq 0.4\ \% , \quad p_C = \tan\delta \leq 0.4\ \% ,$$

$$V_t (f_0) / V = 1 / Q_0 = p_L + p_C \approx 0.8\ \% .$$

If a test object is connected ($C \neq 0$), output voltage and frequency will both decrease, assuming that the input voltage V_t is kept constant by means of a suitable step transformer and that a lower frequency is applied according to resonance with the higher value of capacitance ($C + C_p \rightarrow f < f_0$). The test current I increases partly by shifting of the initial inherent current (I_0) and partly by the higher input current (I_L). Rising current consumption leads to an input current increase proportional to the frequency decrease:

$$I_L (f) / I_0 = (f / f_0)^{-1} = \sqrt{1 + C / C_p} .$$

The frequency regulation range between f_0 (max.) and f_1 (min.) determines the allowable load capacitance. With $f_0 / f_1 = 2$, the load capacitance may go as high as 3 C_p in an ordinary coupling mode (fig.2), or to a maximum of 4 C_p if the parallel capacitor is omitted. A rather high frequency regulation ratio of $f_0 / f_1 = 2$ has been chosen for economical reasons. The power ratings of the capacitor C_p and the inductor L respectively amount to P_0 (maximum at frequency f_0 with no-load) and 2 P_0 with maximum input current I_L at minimum frequency $f_1 = f_0 / 2$. Approximately the same proportion as capacitive/ inductive power ratings (1/2) is valid for cost and weight figures. With a higher capacitor rating C_p / C, a lower frequency ratio f_0 / f_1 would be realized.

The HV-quadripole L, C_p has to also transmit some active power, i.e. a resistive component

$$P_a(f) = p_R \times P_0(f_0)$$

to the branch of current I which is essentially reactive due to the capacitance C. In the case of a constant input voltage (reference), the output voltage will be lowered according to the following equation, when moving from no-load state (f_0) to load (f):

$$\frac{V(f)}{V(f_0)} = \frac{p_L + p_C}{p_R(f/f_0) + p_L(f/f_0)^{-1} + p_C(f/f_0)^2}$$

with V_t = const.

It means that the voltage changes very little if the test object is of high quality like most GIS- or PE- dielectrics, for instance with $f_0 / f_1 = 2$:

$p_R = 0$, $p_L = p_C = 0.4$ % $\rightarrow$ $V(60) / V(120) = 8/9$.

Transmitting active power P_a will, however, influence the voltage drop to be expected due to the term p_R in the above equation. This means that with higher values of the inherent power and quality (P_0, Q_0) higher losses can be transmitted at a reasonably low level of input voltage V_t.

DESCRIPTION OF A SUITABLE KIT SYSTEM

Key Specification of a Design in Six Parts.

Following the previous general considerations three different parts of the circuit had to be specially designed in order to give maximum power (set 1) at reasonable weight. These parts were labelled "drive" for the primary generating power source, "reactor" for the main compensating inductance and "capacitor" for the parallel-coupled additional capacitance. For better adapting the weight of the equipment to test cases of moderate requirements in voltage and power, a second line of components was designed for minimum weight (set 2) at lower power ratings. All six parts are specified in table I. They build up the ordinary kit line described in the next chapter (table II).

Alternator Drives. The powerful drive type DAT (set 1) consists of a six-cylinder Diesel engine coupled to a three-phase asynchronous alternator [4]. Its frequency range covers 50 to 150 Hz at 1500 to 3000 rpm with switchable pole numbers four to six. It is combined with an output transformer of either switchable step positions 1.2 to 5 kV or larger scale series/parallel connections 5/10/20 kV (as option). The resonant load with a certain capacitive power factor being connected to one pair of phases, and the regulated capacitor-excitation working on a different pair of alternator phases, the negative-sequence field may be strongly reduced so that a close to three-phase operation mode of the machine is realized [4]. Full instrumentation and protective means are integrated. The driving set may be remote controlled by push-buttons (feedforward) and by automatic electronic regulation (feedback). It may also be operated as a twin-engine set. The independence from any mains-supply must be regarded as an advantage because sufficient power is often not readily available on site. A simplified structure is shown in the figures 3 and 5.

Mains - independence is not required for the small size drive type MG (set 2). The MG-alternator (motor-generator set, fig.2) is designed as a two-pole single-phase synchronous machine reaching up to 125 Hz at 7500 rpm. It is driven by a three-phase induction motor from the mains. A continuously variable transmission gear affords the speed tuning. The outfit includes a two-steps dc-excitation, a switchable output transformer 0.3 to 3.6 kV and economical instrumentation built-in.

Reactors. The lay-out of the reactors is based on a rod-type iron core centred within a pair of twin-coils. The active parts are immersed in a cylindrical oil-filled resin tank of minimized dimensions. The high power version type HPR (1) includes an intricate system of electric field control which is not required for the small size type IND (2). Peak power ratings mean maximum voltage and maximum intermittent test current allowing three consecutive tests of one minute at maximum power in a day, limited by the heat capacity of the coils. Cooling down to ambient takes six hours (2) to twelve hours (1).

Capacitors. The rated capacitor voltage has to be understood as the nominal value which can be applied continuously. This rating determines the line of complete assemblies (types LC-50 to LC-600, see table II). The rated voltage may be exceeded with an adequate electrode shielding (withstand tests), or it shall be reduced one step if necessary for PD-measurements. The composite type COMP (1) is made of a multipack bank in cylindrical array, the minor type CAP (2) being a single unit. Both types have insulated voltage measuring taps. A separate voltage divider if needed may be assembled of single capacitors as taken out of the package-type COMP.

A Line of Standard LC-Circuits.

For many applications of moderate power demand standardized resonance equipment will do. They may replace a conventional test transformer installation if frequency regulation up to a ratio of $f_0 / f_1 = 2.5$, as described in this paper, is tolerable. The voltage line of table II uses all six components of table I by series-connection of various reactive components within the L- or C_p-paths, and by supplying the HV-quadripole with an appropriate primary source of types MG or DAT. The kit structure brings about some other advantages besides optimization of weight, which are worth mentioning e.g. lower price through higher manufactured unit number, an easier spare parts disposition, and a high degree of overall-flexibility.

General Application Features.

Overall flexibility means that sticking to standard equipment according to table II is not recommended if challenging requirements arise which exceed the voltage or power of the standard program. Of course, it is possible to augment the range of voltage or power by simply using more than three reactors in series (i.e. up to 1000 kV with four reactors), or by parallel coupling of up to ten reactors (see

Table I . Specification of Kit Modules

Component		DRIVE		REACTOR		CAPACITOR	
Size: big (1), small (2)		1	2	1	2	1	2
Type		DAT	MG	HPR	IND	COMP	CAP
Power rating	kVA	100	10	2500	500	630	225
-at rated frequency	Hz	90	90	90	90	120	120
-at rated voltage	kV	1.2-20	0.3-3.6	250	50	200	50
Weight	kg	1850	420	420	125	250	50
Specific properties,							
-capacitance	nF					21	120
-inductance	H			50	15		
-regulation range	Hz	50-150	50-125				
Dimensions	mm						
-diameter				705	430	750	300
-lenght		2200	1100				
-width		1100	800				
-height		1400	1100	770	470	850	700

Table II . Standard LC - Equipments

Type		LC - 50	LC - 100	LC - 200	LC - 300	LC - 400	LC - 600
Rated voltage	kV	50	100	200	300	400	600
Capacitance C_p	nF	120	60	30	15.5	10.5	7.0
Inductance L	H	15	30	65	106	106	160
No-load frequency f_o	Hz	120	120	115	125	150	150
Inherent power P_o	kVA	225	450	850	1100	1600	2400
Capacitor types		CAP	2xCAP	4xCAP	2xCAP+COMP	2xCOMP	3xCOMP
Reactor types		IND	2x IND	IND+HPR	2xHPR	2xHPR	3xHPR
Drive type		MG	MG	MG	MG	DAT	DAT
Weight of equipment	kg	600	800	1200	1650	3200	4000
Transportation mode		in VAN				on TRUCK	

examples fig.3 to 5). Extensions of the kind do not lead out of the specified six-component frame of table I. Even multiple energy supplies may be provided (twin- engine set 2xDAT).

Field experience with ac-tests of high power has shown some outstanding properties compared with other procedures of on-site insulation testing (impulse or dc voltages et cetera). The peculiar advantages in handling are

- no charging of proximate conductive parts. The testing installation as well as the test object are dead and grounded once the engine has been turned off.
- no need of any external energy. The equipment can be used with poor mains power supply, in narrow spaces and in adverse weather (see example fig.4).

As there is only a cable connection of small cross section between the engine (on truck) and the composite multiple reactor (unloaded), the testing arrangement is flexible. A typical cable test (fig.4) can be installed within three hours, a test engineer, a truck driver and a fork-lift being required to do the job.

FIELD EXPERIENCE IN TESTING LONG HV-CABLES

Modern HV-cables with a polymer dielectric usually pass a quality certifying ac-test in the factory on manufactured partial lengths of several hundred meters. An additional withstand test on site carried out on the whole assembly of installed underground power line is considered necessary, but dc-voltage tests according to common practice up to now do not comply with the actual electric stresses of an ac-operated cable line [5]. Testing with an ac-voltage of close to power

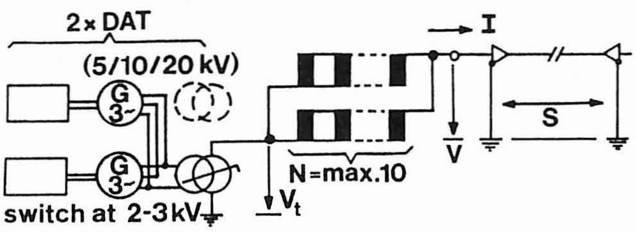

Fig. 3 . Cable-Test Connections with Single-Stage Reactors for Short Test Duration, T = 1...5 min.

2xDAT Twin-engine set with common step transformer.
V Test voltage max. 230 kV, if T = 1 min.
I Test current max. 100 A.
N Number of parallel coil paths max. 10.
S Test length of cable phases max. 5 km.

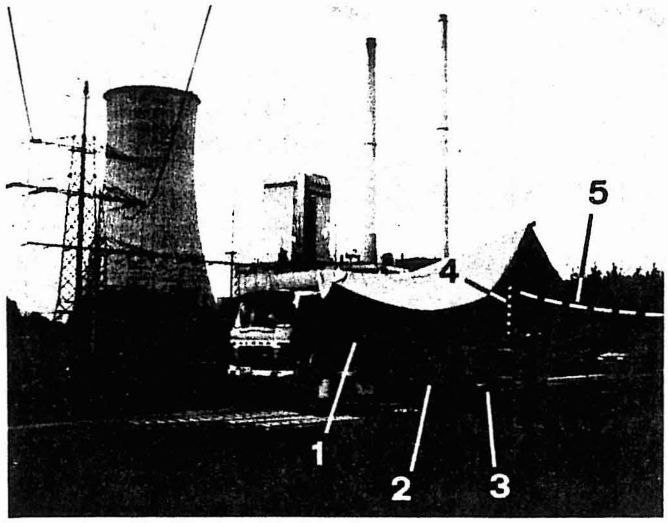

Fig. 4 . Two-Stage Testing on Site *Schwandorf, Bayernwerk AG, Munich (FRG),* with Live HV-Parts Unloaded and Ready for Test under Rain Sheltering Tent:
V = 160 kV, T = 15 min, N = 4, S = 2.2 km, f = 60 Hz.

1 One engine type DAT staying on truck.
2 Voltage dividing capacitor 1.5 nF.
3 Four double reactors (eight type HPR).
4 Break-down wave protection.
5 Wire cord leading to cable terminating rack.

line frequency instead of dc exhibits a most promising procedure since high power resonant test equipments are available (fig.3). In this application of the power supply kit system several parallel-coupled reactors of the HPR-type are connected in series with a total test length S of the cables. The expense of test material is proportional to the number of parallel coil paths N, single-stage reactors (fig.3) being used for short test duration (T = 1 to 5 min) and double reactors (fig.4) for longer duration (T = 15 to 20 min).

Most experience refers to power lines of 110 kV nominal line-to-line voltage. Test voltages applied against ground range from 123 kV, 5 min (IEC-recommendation) to 230 kV, 1 min (maximum according to coordination level of 110 kV systems [3]). Longer test times have been asked for at V = 160 kV (power line 110 kV, fig.4) as well as V = 300 kV (power line 220 kV [5]). Parallel coupling of single-stage reactor units according to fig.3 yields the highest benefit of the equipment as total expenses are optimized at equal shares of the reactive volume and the engine drive. The heat capacity of the coil will then be fully used at the peak power rating (V^2/f = max.) and minimum time (T). The admissible heat storage of each reactor may be characterized by
$(V/f)^2 \times T$ = const.

Nearly full rated power of the cable-testing equipment will be required in an acceptance test to be carried out shortly, on behalf of *Energieversorgung Schwaben, Stuttgart (FRG).* The following test data have been pre-calculated :
V = 230 kV, T = 1 min, N = 7 (single-stage), S = 3.8 km/phase
I = 73.5 A, f = 85 Hz,
P_a = 130 kW (twin-engine set), P_r = 17 000 kVA.

TESTING OF AUTO-EXCITED TRANSFORMERS

Due to the non-linearity of magnetizing currents and of the iron losses in a transformer core, both strongly depending on the degree of saturation, most stringent conditions are found when testing transformers outside a factory lab. Since transportable regulated supplies present considerable source impedance (not so with operation from the mains), severe distortions of the voltage wave and even unstable ferroresonance may occur, leading to supply equipment of unstable behaviour if too small. This difficulty has to be overcome by increasing frequency for a lower magnetizing current and by reactive compensation (resonance) for up-graded power (reduction of source impedance).

For PD-measurements on site, a pair of potential transformers, for instance, may be disconnected from the line and coupled in parallel thus forming a loop of primary HV-windings for bridge-measuring circuitry. Without more details on PD, it is worth mentioning that such a pair of instrument transformers may be excited through their secondary windings by the speed varying motor-generator type MG. With instrument transformer ratings of 2×5 kVA, 230 kV/$\sqrt{3}$: 100 V/$\sqrt{3}$ a very steady voltage regulation was achieved which gave a secondary test voltage of 115 V, 80 to 90 Hz at nominal operation voltage level (two secondaries in series). As an improvement of regulation features, a low voltage choke coil of negligible power (about 10 kVA, same as supply) has been added in parallel. This may show that a resonant device of rather broad band width will do because there is no need of a high Q-factor, the power ratings of the supply and the test object being of the same order (P = 10 kVA).

A big power transformer, however, needs a narrow-band supply of sufficient reactive power in order to transmit an appreciable iron loss power from the drive to the core at reasonably low voltage of the primary source. Power transformer ratings may reach as much as 1000-times the ratings of the supply drive (fig.5). A prospective no-load test would be made by feeding the twin-engine set type 2xDAT through reactor bank L_2 into HV-terminal V_2 while the winding capacitance C_w is backed-up by an additional capacitor C_1 connected to terminal V_1. Feeding into the terminal of highest voltage V_1 across another reactor L_1 would be possible if there is no tapping. Parallel feeding into the tertiary winding at voltage V_3 is not recommended because of the inherent out-of-resonance short-circuit conditions to be expected.

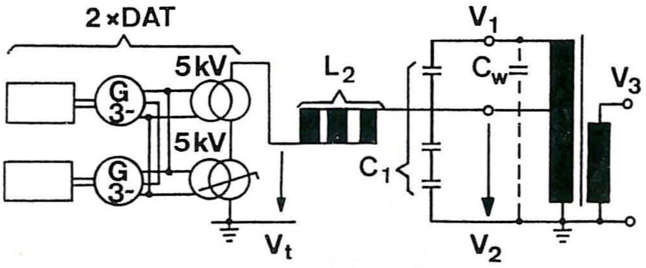

Fig. 5 . No-Load Test of an Auto-Excited Transformer, Transformer Rating P = 100 MVA Single-Phase, 550/$\sqrt{3}$ - 230/$\sqrt{3}$ - 13.8 kV, Consumption about 400 kVA/80 kW at 15 kV, 60 Hz Tertiary Input.

2×DAT	Twin-engine set 200 kVA, 10 kV.
L_2	Over-compensating reactor bank (type HPR).
C_1	Backing-up capacitor type 3×COMP.

A rough calculation of the balance of resonance and of losses may show how no-load testing on big transformers can be made, using the data given in fig.5.

Test voltages at 1.2-times nominal level:

Primary winding .... V_1 = 380 kV
Secondary winding .... V_2 = 160 kV
Tertiary winding .... V_3 = 16.5 kV
Winding capacitance estimated .... C_w = 10 nF
Parallel-capacitor 3×COMP,
series-connected 21/3 .... C_1 = 7 nF
Series-reactors HPR,
one-stage parallel 50/3 .... L_2 = 17 H
Operating frequency,
set to resonance ..... $f = V_2/V_1/\sqrt{L_2\,(C_w+C_1)}/(2\pi)$ = 125 Hz
Wave impedance,
at secondary tap .... $Z_2 = \sqrt{L_2/(C_w+C_1)} \times V_2/V_1$ = 13.3 kΩ

Test current .... $I_2 = V_2 / Z_2$ = 12 A
Reactive power ...... $P_r = V_2 \times I_2$ = 1920 kVA
Transformer iron losses at 125 Hz .... 75 kW
Copper losses of reactors...................... 7 kW
Dielectric losses totally .... 10 kW

Total active power ..... P_a = 75 + 7 + 10 = 92 kW
Q-factor .... Q = 1920 / 92 = 20
Min. input voltage ..... V_t = 160 / 20 = 8 kV

CONCLUSION

It was intended to show that resonance, although mostly a nuisance to stay away from in power engineering, is an imperative condition for efficient high voltage ac-testing. This has been demonstrated in three application ranges:

- In the field of large-scale tests of moderate power demand, including normal GIS-substations on site, an extremely light-weight power supply kit system has been presented which offers high flexibility and low cost compared with a testing transformer.
- In the field of cable-testing, some examples of high power application are given which may have an influence on test requirements of installed cable lines.
- A prospective transformer test has been sketched which may stimulate new ideas for the monitoring of transformer insulations on site, i.e. PD-measurement.

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HEINZ G. GERLACH born 1927, regularly attended the Technical University of Karlsruhe (Germany 1947-51) before starting his career as Dipl.-Ing. in electrical power engineering at the test labs of *MFO* Zurich-Oerlikon (later *BBC*, now *ABB*). Employers encouraged him to take a degree aft years, as Dr.-Ing. from his university (Karlsruhe 1966) wi a paper about enhanced studies on the thermal behaviour of induction motors.

In the persistent employ of a couple of Swiss industrial companies (1951-69), he gathered a broad pattern of applied engineering practice (i.e. rotating machinery, electro-mechanical or electronic devices, production engineering and electrostatic flue gas filters) before recovering a scientific destination. He was then installed as assistant professor on electrical machines at the Swiss Federal University, ETH Zurich (1970-76). In his late activity, he has been in charge of the "Commission of the Swiss Electrotechnical Association and Swiss Association of Producers and Distributors of Electricity on High Voltage Technology", German abbreviation *FKH* (1980-90 after an introductory period 1977-80).

When retiring from *FKH* he joins, as a senior managing director, with *HANS KULL AG* Derendingen (Switzerland), manufacturers of resonant power supplies.