# Considerations in the Specification of

# ***High Voltage Test Systems***

By: Jeffrey A. Britton
Assistant Chief Engineer
Phenix Technologies Inc.

## Fundamental Classification of High Voltage Test Systems

**- High Voltage AC Test Systems**

**- High Voltage DC Test Systems**

## Types of High Voltage AC Test Systems

Note: For the context of this discussion, "High Voltage" is generally considered to be any AC or DC voltage in excess of 20 kV.

**- AC Dielectric Test Systems**

**- Resonant AC Test Systems**

## Issues to Be Considered in the Specification of a Standard AC Dielectric Test System vs. An AC Resonant Test System

***- Load Type (Capacitive / Resistive):***

- **Standard AC Dielectric Test Systems may be used to test Capacitive or Resistive test objects, and may or may not include reactive compensation.**

- **Resonant AC Test Systems are exclusively for high voltage testing of Capacitive test objects.**

- **A standard AC Dielectric Test System must be used for loads which have time varying characteristics, such as polluted insulator tests.**

***- Power Requirements:***

- **Standard AC Dielectric Test Systems which are not reactively compensated require an input service equal to the output HV testing kVA of the test system, plus test system losses.**

- **AC Resonant Test Systems are typically employed when test objects represent a relatively large capacitance, such as long lengths of HV cable or large generator or transformer windings.**

- **The required input power is reduced to only that of the ohmic (real power) losses within the system, typically 1/10$^{th}$ to 1/40$^{th}$ of the required HV testing kVA.**

***-Limitation of transients during specimen failure:***

- **Generally speaking, destructive transients are reduced with AC Resonant Test Systems as compared to standard AC Dielectric Test Systems, as the amount of follow through energy from the line is limited by the impedance of the regulator and exciter transformer.**

- **Overvoltage transients are virtually eliminated in Series AC Resonant Test Systems, as the voltage is only present when the resonant condition exists. The resonant condition is immediately disrupted when a specimen failure occurs, and transient overvoltages are not produced.**

***- Waveshape requirements, distortion, harmonic content:***

- **Generally speaking, AC Resonant Test Systems produce a less distorted sinusoidal HV output than a standard AC Dielectric Test System of similar ratings.**

- **In practice, total harmonic content is typically less than 5% at full load for traditional standard AC Dielectric Test Systems. For AC Resonant Test Systems, total harmonic content is typically much less than 1% at full load.**

- **Waveform distortion produced by Standard AC Dielectric Test Systems in practice becomes less prominent as the kVA rating of the system increases.**

- **Higher output waveform distortion in standard AC Dielectric Test Systems also occurs as the step-up ratio of the transformer increases.**

***- Initial System Costs***

- **Generally speaking, the purchase of an AC Resonant Test System represents a higher initial cost than a standard AC Dielectric Test System with similar ratings. This is due to the high design and manufacturing costs for the variable - gap HV reactor.**

- **As the amount of required HV testing power increases, AC Resonant Test Systems become increasingly competitive with standard AC Dielectric Test Systems. In some cases it is possible to supply an AC Resonant Test System more economically that a standard AC Dielectric Test System. Each customer's testing requirements must be evaluated individually to determine an optimum solution.**

# Issues to Be Considered in the Specification of a Standard AC Dielectric Test System

## - *Physical Package: Tank Type vs. Insulating Cylinder Type*

- **In General, there are two basic construction techniques used in the design of oil insulated high voltage test transformers used in AC Dielectric Test Systems. These are: Tank Type and Cylinder Type.**

**Factors Influencing The Choice of Physical Packaging for HV Test Transformers**

## - *Required Output Voltage*

### - Tank Type HV Test Transformer

- **In this design, the oil insulated high voltage transformer is contained within a conducting vessel, typically a welded steel tank.**

- **The transformer core is connected to the same potential as the tank body. For a single transformer (non-cascaded transformer) design, the tank is normally grounded to earth at the same physical location as the return side of the test specimen.**

- **The HV output is brought out via HV bushing. The fact that a bushing output is required limits the voltage magnitude which can be developed in a single tank. Voltages in excess of 350 kVrms start to become impractical, as the physical dimensions of the output bushing become difficult to deal with.**

- **Cascade connections of multiple Tank Type Transformers in series are possible to obtain voltages higher than 350 kVrms, but are usually impractical due to the extreme expense involved in building corona shields and insulating structures to support higher stages.**

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**- Cylinder Type HV Test Transformer**

- **In this design, the oil insulated high voltage transformer is contained within an insulating cylinder, typically fiberglass or, for small transformers rated equal to or less than 10 kVA and 200 kV, PVC.**

- **On relatively large transformers (in excess of 10 kVA and 200 kV), the top and bottom of the cylinder are capped with conducting header plates. These plates often serve directly as the output terminations.**

- **The transformer core may be tied to the bottom header plate potential, or may be tied to an intermediate high voltage potential within the cylinder.**

- **The HV output is normally taken from the corona rings which are bolted to the top header plate, or from an output spinning bolted through the top plate of the insulating cylinder on small transformers. Since no bushing is involved, there are no voltage limitations imposed by the output termination.**

- **Cylinder type HV transformers can easily be designed to be stacked and wired in cascade configurations. This allows for generation of test voltages in excess of 1 MV.**

***- Required Output Power***

- **In cases where a condenser type porcelain insulated output bushing is used, care must be taken to include the capacitive load imposed by the bushing on the high voltage transformer and regulator. This may be significant with a relatively high voltage but low power test system.**

***Example:***

**Consider a 196 kV Class HV Bushing, being used as an output termination on a Tank Type Transformer, whose output ratings are: 350 kVAC @ 100 kVA, 60 Hz., 1 Hour On / 1 Hour Off Duty, and 70 kVA Continuous Duty. If the Capacitive tap on the HV Bushing has a nominal capacitance of 400 pF to ground, what percentage of the HV transformer's 1 Hour On / 1 Hour Off output kVA rating is consumed by the HV Bushing. What percentage of the HV transformer's Continuous Duty Rating is consumed by the bushing?**

***Solution:***

**The capacitive reactance presented by the bushing at 60 Hz. is:**

$$X_c = \frac{1}{2\pi fC} = \frac{1}{(2)(\pi)(60)(400x10^{-12})} = 6.63M\Omega$$

**The kVA load imposed upon the HV Test Transformer at 350 kVAC is:**

$$LOAD = \frac{V^2}{X_c} = 18{,}476VA \approx 18.5kVA$$

**This represents 18.5% of the HV Test Transformer's 1 Hour On / 1 Hour Off Duty output kVA, and 26.4% of the HV Test Transformer's Continuous Duty output.**

**If 100 kVA of HV Testing Power was required, the HV Test Transformer, Regulator and Input Service would have to be sized to cover the load presented by the HV Bushing.**

- **In cases where a relatively high output voltage is required at a relatively low kVA, a cylinder is often a better choice, as there are no power losses to a HV bushing.**

- **In theory, if proper cooling is provided, there is no upper kVA limit to either design.**

## - *Duty Cycle and Thermal Issues*

### - Tank Type HV Test Transformer

- **Tank Type HV Test Transformers are better suited for continuous or long term duty operation if no external cooling system is to be provided.**

- **The steel tank design exhibits better heat dissipation characteristics than a fiberglass or plastic cylinder, which tends to limit heat transfer from the oil to the outside.**

- **To increase kVA capacity or duty cycle in a given physical size, additional cooling measures may be used to transfer heat away from the coils. Possible measures include:**

  1) **Use of radiators on the tank to increase the effective surface area of the tank for cooling purposes. This is the most economical and easily implemented solution. No customer action is required.**

  2) **Use of radiators on the tank in conjunction with fans outside the tank. This is also quite economical and easy to implement, and only requires the customer to supply AC power to the fans.**

- **Although more elaborate cooling systems involving heat exchangers can be used if more cooling is required, such measures are very seldom required for tank type HV test transformers.**

- **Specification of actual duty cycle is extremely important. Proper specification of duty cycle will lead to an optimal solution for the customer in terms of cost, physical dimensions, and performance.**

## - Cylinder Type HV Test Transformer

- Cylinder Type HV Test Transformers are not generally suited for continuous or long term duty unless external cooling is provided. This is not normally a limitation however, as most hipot tests performed with this equipment are of short duration, often lasting only a few minutes.

- Higher kVA capacities and increased duty cycles up to and including continuous duty are available with the use of external cooling systems. Possible measures include:

  1) Use of an oil-to-air heat exchanger external to the tank, to exhaust heat into free air. This is somewhat costly, and the customer must provide power to the oil pump(s), power to the fan(s) on the heat exchangers, and plumbing to carry the oil from the tank to the heat exchanger. Such measures are normally required only for systems designed to operate for extended periods of time.

  2) Use of an oil-to-water heat exchanger external to the tank, to exhaust heat either into a continuous cool water supply or into a re-circulated water supply cooled by a chiller if a continuous cool water supply is unavailable. This is the most expensive and difficult to implement solution, as the customer must provide power to the oil pumps, plumbing for the cooling water, and either a continuous supply of cooling water or power to operate a chiller. This measure would normally only be required for a very large unit designed to operate at true continuous duty.

- Specification of actual duty cycle is extremely important. Proper specification of duty cycle will lead to an optimal solution for the customer in terms of cost, physical dimensions, and performance.

## Factors Influencing The Use of Fixed Reactive Compensation in AC Dielectric Test Systems

### *- Type of Load*

- Reactive Compensation is only an option with stable capacitive test objects. With a few exceptions, almost all test objects represent capacitive loads under hipot test.

- Notable exceptions are switchgear insulators, and fiberglass bucket truck booms, whose resistive leakage current component is larger than the capacitive charging current. These test objects appear as very light resistive loads under hipot test.

- If the system is designed to draw full load current at both no load, and at full capacitive load, the only difference being the phase angle of the input current with respect to the input voltage, any pure resistive component of current will overload the primary of the test system. Capacitance is therefore required on the output.

- AC Dielectric Test Systems with reactive compensation should not be used to test loads with time varying characteristics, such as polluted insulators. The magnitude and phase angle of the load current varies with these types of loads, and reactive compensation is not beneficial.

## *- Form of the Reactive Compensation*

### - Use of External Fixed Low Voltage Reactors

- **Use of one or more fixed value low voltage reactors connected in parallel with the primary of the HV Test Transformer is one of the most versatile solutions for reactive compensation in AC Dielectric Test Systems.**

- **Stepped variable compensation is possible through power off switching of different reactance values. Using this method, near 100% compensation can be achieved using the proper combination of compensating reactors.**

- **Protection circuitry is required within the test system to guard against undesired resonance between the compensating reactors and the capacitive test object. Failure to include this protection can result in large circulating resonant currents within the system, which can damage the power components in the primary circuit.**

- **This type of compensation is quite versatile in that resistive loads can also be tested at powers up to the rated power of the regulator, by simply not pulling in any of the fixed reactors. In this mode the test system may be operated as a normal AC Dielectric Test System without reactive compensation.**

- **Switching of the compensating reactors must always be done with the power off, and may either be accomplished manually, through physical reconnection of reactors, or electrically through the use of contactors.**

- **With this arrangement with proper sizing of the compensation reactors, the regulator and input service to the test system can be sized as small as 10% of the required HV testing power.**

## - Use of a Fixed Airgap in the Core of the HV Test Transformer

- **Placement of a fixed airgap in the magnetic core of the HV Test Transformer is a very common technique for achieving 50% reactive compensation.**

- **If only a single level of compensation is utilized, 50% compensation maximizes the benefit over the entire load range of no load to full capacitive load, by cutting the size of the regulator and input service in half.**

- **In this case, the amount of reactive compensation is fixed.**

- **This type of test system may only be used for capacitive test objects.**

- **This type of system is designed to draw rated input current both at no load, and at full capacitive load. The phase angle of the input current changes from near ninety degrees lagging the input voltage to near ninety degrees leading the input voltage as the capacitive load is increased from zero to rated load.**

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## - Use of a Fixed HV Reactor in Parallel With the Test Object

- This method of reactive compensation is normally the most expensive and difficult to implement, as it requires high voltage reactors, rated for the maximum test voltage, to be placed in parallel with the test object.

- Stepped variable compensation is possible by placing different fixed reactors in parallel with the test object. This is similar to AC Resonant Test System operation, without the ability to continuously adjust the level of compensation as in a Resonant Test System.

- The high expense of this technique coupled with the relatively low level of versatility normally makes this method of compensation unattractive as a solution.

***- Available Input Power***

- **The amount of available input power to the test system often determines the type of reactive compensation required.**

- **If more HV testing power is required than is available from an existing input service, and the test load is largely capacitive, reactive compensation using one of the previously mentioned techniques may be the solution.**

- **Depending on the technique used and the type of objects being tested, it may be possible reduce the required input service to as little as 10% of the required HV testing power.**

- **Typically, using the most common technique of including an airgap in the core of the HV Test Transformer, the required input power will be reduced to approximately 50% of the required HV testing power. This reduces the size of the regulator, input circuit breaker, and contactors as well.**

***- Available Output Power***

- **When using fixed compensation, it is important to recognize that output current capability varies with output voltage. This means that the available HV testing power varies non-linearly with output voltage.**

- **It is important to understand the output characteristics of a reactively compensated AC Dielectric Test System, as customers often incorrectly assume that maximum rated output current is available at any output voltage.**

- **In practice, in an AC Dielectric Test System supplied with 50% fixed reactive compensation, maximum rated output current is only available at a single load point: tuned to the proper capacitance at maximum rated output voltage.**

- **The following illustrative example, which shows the calculations, will help to explain the actual operation of an AC Dielectric Test System designed with 50% reactive compensation on the primary side of the HV Test Transformer.**

**Example:**

**Consider an AC Dielectric Test System rated at 100 kV output at 100 kVA, 50 Hz. The regulator is rated 400 V, 50 Hz. input, and 0 - 400 V, 0 - 50 kVA output. A fixed primary reactor rated at 50 kVAR at 400 V, 50 Hz. is connected in parallel to the primary winding of the HV Test Transformer.**
**Neglecting real and reactive power losses within the system, what are the maximum available HV testing power and current at 100 kV? At 50 kV?**

**Solution:**

**The easiest way to understand the operation of a reactively compensated AC Dielectric Test Set is to look at the system from a power perspective.**

**The HV testing power available at a given voltage is the sum of the available regulator output power and the available compensation available from the fixed reactor at that voltage.**

**The regulator provides variable voltage at constant current. The output power of the regulator is therefore proportional to output voltage. In this case, rated output current for the regulator is calculated as:**

$$I_{reg} = \frac{RatedPower}{RatedVoltage} = \frac{50{,}000VA}{400V} = 125A$$

**The output power of the regulator as a function of regulator output voltage is expressed as:**

$$OutputPower = OutputVoltage * 125[VA]$$

**The compensation available from the fixed reactor is expressed as:**

$$Comp = \frac{OutputVoltage^2}{X_r}[VA]$$

$X_r$ **is the inductive reactance of the compensating reactor, in ohms. This may be calculated from the data given as follows:**

$$X_r = \frac{RatedVoltage^2}{RatedPower} = \frac{(400\text{V})^2}{50{,}000VA} = 3.2\Omega$$

**Therefore the available compensation from the fixed reactor is expressed as:**

$$Comp = \frac{OutputVoltage^2}{3.2\Omega}[VA]$$

**The available HV testing power is then:**

$$TestPower = (OutputPower) + (Comp)[VA]$$

$$TestPower = (OutputVoltage * 125) + (\frac{OutputVoltage^2}{3.2})[VA]$$

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**Neglecting system losses, at 100 kV output, the regulator output voltage will be rated voltage (400 V). The available HV testing power is therefore:**

$$TestPower = (400)(125) + \frac{400^2}{3.2} = 100{,}000[VA]$$

**This equates to an available current of 1 A at 100 kV.**

**At 50 kV, 1/2 of rated output voltage, neglecting system losses, the regulator output voltage will be 1/2 rated voltage (200 V). The available HV testing power is therefore:**

$$TestPower = (200)(125) + \frac{200^2}{3.2} = 37{,}500[VA]$$

**This equates to an available current of 0.75 A at 50 kV.**

**This demonstrates the principle that rated current is not available from a reactively compensated AC Dielectric Test System at all voltages.**

- **For each reactively compensated AC Dielectric Test System, a plot may be made which describes output current and output power as a function of output voltage. This plot will vary with the percentage of reactive compensation.**

## - *Initial System Costs*

- **The effect of including reactive compensation on the initial cost of an AC Dielectric Test System varies, depending on the type of compensation used, and the size of the test system.**

- **Including 50% reactive compensation in the form of an airgap in the core of the HV test transformer is the most economical solution. This solution is often less expensive than a normal AC Dielectric Test System with no compensation. The savings are realized in the reduction in the size of the regulator, primary circuit breaker and contactor, and primary winding of the HV test transformer.**

- **Including fixed reactive compensation in the form of a single compensating reactor connected in parallel with the HV test transformer will typically cost about the same as a normal AC Dielectric Test System with no reactive compensation. In this case, there is no cost savings in the HV test transformer itself, and any savings in regulator costs are usually absorbed by the provision of the additional low voltage reactor.**

- **Including stepped variable reactive compensation in the form of several low voltage reactors of various compensation values typically adds considerable versatility to the test system, and also adds cost. Although there is some savings in the reduction in the size of the regulator, this is normally more than absorbed by the cost of the additional low voltage reactors, the contactors to switch them in and out, and the associated control and protection system costs.**

- **Reactive compensation in the form of HV compensating reactors connected in parallel with the test object typically adds considerable cost to the system. Generally speaking, the benefit derived by this solution does not justify the cost.**

- **In all cases where reactive compensation is used, there should be some savings in reduction of the required input service to the test system. This is an indirect savings, but a savings just the same.**

***- System Operating Costs***

- **Maintenance costs for compensated and un- compensated AC Dielectric Test Systems are very similar, as very little maintenance is required for these systems.**

- **The regulator is the only main component which requires periodic maintenance. Decreasing the size of the regulator by using reactive compensation may provide a small decrease in maintenance costs for reactively compensated systems.**

- **For very large AC Dielectric Test Systems, there may be a considerable long term savings in power cost for customers whose power billing includes a power factor penalty.**

**Factors Influencing the Type of Regulator Used in an AC Dielectric Test System**

***- Solid State Regulators***

- **Not traditionally used in high power high voltage AC test systems**

- **Solid State Regulators typically generate undesireable harmonic content, and distortion of the output voltage from that of a true sinewave.**

- **Introduction of high frequency noise can also be a problem, which is not acceptable for conducting HV withstand testing and making partial discharge measurements.**

- **The ability of solid state components to withstand the violent transients which can be produced during HV test specimen failures does not match that of variable transformers.**

## *- Variable Transformer Type Regulators*

- **Traditionally used in high power high voltage AC test systems. Some of the reasons why variable transformers continue to find favor in high voltage AC testing are:**

  1) **Variable Transformers represent a well defined technology, with many years of proven performance in this application.**
  2) **Variable Transformers exhibit high reliability with a relatively low amount of required maintenance.**
  3) **The simplicity and relatively low cost of variable transformer design and production makes them attractive for use in custom test systems.**
  4) **Modular designs allow for regulation of voltage at practically unlimited power levels.**
  5) **Variable transformers exhibit a high tolerance for short term overloads, making them ideal for use in AC Dielectric Test Systems where a high power requirement exists for a short time.**
  6) **Variable transformers exhibit a high tolerance to the transients which are produced during test specimen failures (flashovers).**
  7) **Variable transformers do not contribute to harmonic content, nor produce waveform distortion. In fact, certain type of variable transformers, especially two winding variable transformers (non-autotransformers) provide a line filtering action which blocks the passage of high frequency disturbances existing on power line.**

- **Several different types of variable transformer designs are in common use in AC Dielectric Test System regulators. The type of variable transformer used if most often determined by application. Designs commonly in use include Toroidal Variable Autotransformers, Column Type Variable Transformers, and Thoma Type Variable Transformers.**

## - Characteristics and Applications of Toriodal Type Variable Autotransformers

### - Main Characteristics

- A Toroidal Type Variable Autotransformer is constructed by winding a single layer of magnet wire onto a toroidal core. A sliding or rolling brush assembly moves radially over a surface of the winding which has been ground to expose the conductor.

- A "quasi stepless" variable sinusoidal voltage is available at the brush, with negligible distortion.

- The series impedance will typically range between 30% and 1% as the brush position varies from 10% to 100%.

- Voltage resolution is typically around 0.7 Volts / turn.

- Efficiency is normally between 92% and 98%.

- Input voltage ranging between 120 V and 300 V. Units may be connected in series to provide regulation up to 600V.

  - **Theoretically unlimited kVA rating when stacked and ganged.**

  - **In practice, use of Toroidal Type Variable Autotransformers becomes mechanically cumbersome above 200  kVA due to complex motor and chain drive mechanisms required to synchronize and drive the brush holder assemblies.**

  - **A limited amount of voltage step-up may be achieved, approximately 15% - 20%, but this is normally at a somewhat de-rated output current.**

  - **Overload withstand capability is good, but not as good as other types of variable transformers, particularly when sliding contacts are used, as do most U.S. manufacturers.**

- **Applications in AC Dielectric Test Systems**

  - **Input voltages up to 600 V**

  - **In practice, powers up to approx. 200 kVA, at 50% duty cycle. (1 hour on / 1 hour off)**

  - **Single or three phase applications**

## - <u>Characteristics and Applications of Column Type Variable Transformers</u>

- **Main Characteristics**

  - **A Column Type Variable Transformer may either be constructed as a Two Winding Variable Transformer, with a primary and a secondary, or as a Variable Autotransformer.**

  - **Generally speaking, the regulating winding of a Column Type Variable Transformer is constructed by winding a single layer of flat magnet wire on edge onto an insulating tube. A rolling brush assembly moves axially over a surface of the winding which has been ground to expose the conductor.**

  - **Either a primary winding (for Two Winding Variable Transformer designs) or a compensation winding specially designed to reduce series impedance (for Variable Autotransformer designs) wound onto a smaller insulating tube, which fits inside the regulating winding tube.**

  - **These tubes are placed concentrically onto the core steel, which is typically stacked from cut lamination steel. This allows for conventional single phase or three phase core construction.**

  - **A "quasi stepless" variable sinusoidal voltage is available at the brush, with negligible distortion.**

  - **For Variable Autotransformer designs, the series impedance typically ranges between 10% and 1% as the brush position varies from 10% to 100%.**

- **For Two Winding Variable Transformer designs, the series impedance is typically nearly constant as the brush position varies from 10% to 100%, and is usually between 6% and 12%.**

- **Voltage resolution is typically less than 0.7 Volts / turn.**

- **Efficiency is normally between 95% and 98%.**

- **Input voltage ranging between 120 V and 600 V.**

- **Unlimited kVA rating when ganged.**

- **A limited amount of voltage step-up may be achieved, approximately 15% - 20%, but this is normally at a somewhat de-rated output current.**

- **Line separation (isolation) is possible, in the Two Winding Variable Transformer design, which is necessary for some applications.**

- **Excellent overload withstand capability, superior to Toroidal Variable Autotransformers.**

- **More suited to long term testing and heavy industrial use than the Toroidal Variable Autotransformer.**

- **Generally more expensive than Toroidal Variable Autotransformers in applications below 200 kVA.-**

**Applications in AC Dielectric Test Systems**

- **Input voltages up to 600 V**

- **Unlimited kVA rating**

- **Single and three phase applications**

## - Characteristics and Applications of Thoma Type Variable Transformers

### - Main Characteristics

- A Thoma Type Variable Transformer is constructed strictly as a Two Winding Variable Transformer, with a primary and secondary.
- The regulating (secondary) winding is constructed by winding a single layer of non-insulated wire or bar onto a rotating cylinder. A moving brush assembly, which is precisely gear timed to follow the secondary winding, serves as the continuous tapping point to provide a continuously variable, pure sinusoidal waveform without distortion.
- A the primary winding is situated inside the secondary winding, both of which are installed on the center leg of single phase shell type core constructed of cut lamination steel.
- These unit are usually oil insulated, and are contained in welded steel tanks.

- **As the moving brushes do not traverse turns, but track the winding continuously, the Thoma Type Variable Transformer does not generate electromagnetic interference (EMI).**

- **The series impedance is constant as the brush position varies from 10% to 100%, and is usually between 4% and 10%.**

- **Voltage resolution is infinite.**

- **Efficiency typically around 98%.**

- **Input voltages up to approximately 20 kV**

- **Single units up to approximately 2000 kVA are available. kVA rating is unlimited when regulators are ganged in parallel.**

- **Output voltage is usually designed to be 0 to 1000 V, but this can vary somewhat.**

- **Line separation (isolation) is provided.**

- **Excellent overload withstand capability**

- **Suited for long term or continuous operation at full load, with no movement of the brushes.**

- **Based on the two winding design and the core design, which contains an integral airgap, waveform distortion is reduced. The Thoma Type Variable Transformer therefore provides a line filtering effect, beneficial in high voltage testing.**

- **Relatively high reactive excitation current, typically 5% to 10% of rated full load input current.**

  - **Based on the relative complexity, the Thoma Type Variable Transformer is rather expensive when compared to other types of variable transformers. The high kVA capacity and stepless output characteristics however are unmatched by other variable transformer designs.**

- **Applications in AC Dielectric Test Systems**

  - **Input voltages up to 20 kV**

  - **In practice, kVA ratings range from approximately 200 kVA upwards. Maximum kVA is unlimited.**

  - **Single and three phase applications**

## Notes Regarding System Impedance in AC Dielectric Test Systems

### - *General HV Testing*

- **In typical HV Testing applications, a test transformer impedance of approximately 8% to 12% based on the transformer's rated kVA is acceptable.**

- **The relatively high impedance of a standard AC Dielectric Test System transformer helps to limit the energy released during specimen failure. This reduces undesirable damage which may be inflicted on the specimen itself, as well as on the system.**

- **In a typical AC Dielectric Test System, a variable autotransformer is normally used as the regulator. As noted earlier, the impedance of the variable autotransformer varies with brush position, and may range from 1% to as high as 30%, depending on the type of variable transformer used. This is acceptable for most HV testing applications.**

- **Most HV testing loads represent stable capacitive loads before failure occurs. In this case, system voltage regulation does not become an issue, as the output voltage is being directly controlled by either an operator or an automatic control system.**

***-   Special HV Testing***

- **In certain types of high voltage testing, such as testing of polluted or contaminated HV insulators, the test object represents an unstable resistive / capacitive load, whose characteristics are time dependent.**

- **In this special type of testing a very strong test voltage supply is required. Low and constant impedance is needed to maintain a stable test voltage output under conditions of very high and erratic partial discharge.**

- **Special designs are required for the HV transformer and regulator to achieve a low constant impedance. These types of systems are more expensive than normal AC Dielectric Test Systems due to the special design, and the increased physical and electrical strength built into such systems.**

- **The best way to insure optimal function of a given test system is to determine the type of testing to be performed, and include this in the specification given to the equipment supplier in the specification stage of a test system purchase.Issues to Be Considered in the Specification of an AC Resonant Test System**

***-   Physical Package: Tank Type vs. Insulating Cylinder Type***

- **In General, there are two basic construction techniques used in the design of oil insulated high voltage tuneable reactors used in AC Resonant Test Systems. These are: Grounded Tank Type systems and Modular Cascade Cylinder Type systems.**

# Factors Influencing The Choice of Physical Packaging for AC Resonant Test Systems

## - *Grounded Tank Type HV Reactor*

- **In this design the oil insulated high voltage reactor is contained within a grounded conducting vessel, typically a welded steel tank.**

- **The reactor core and drive frame are connected to ground potential within the tank body.**

- **Grounded Tank Type AC Resonant Test Systems may be operated in either series or parallel resonant mode.**

- **The HV output is brought out via HV bushing. The fact that a bushing is required limits the voltage magnitude which can be developed within a single tank. Although higher voltages are possible, voltages in excess of 400 kV start to become impractical, as the physical dimensions of the output bushing become difficult to deal with.**

- **Voltage measurement is usually accomplished via the capacitive tap on the output bushing.**

- **Running in parallel resonant mode, the voltage can be raised to full rated output voltage with no load on the HV reactor. This is useful for calibration of the instruments, as well as for making partial discharge measurements on the test system itself.**

- **Grounded Tank Type Resonant AC Test Systems may be supplied with several output taps, which allow for tuning over a greater capacitance range.**

- **A minimum 20 to 1 tuning range is typical for each output tap supplied.**

- **Partial discharge measurement is normally made via an external coupling capacitor, which may also serve as a preload for series mode resonant operation, in the absence of a test object within the specified tuning range of the HV reactor.**

- **All Phenix Technologies HV reactors are specified to provide exceptionally clean high voltage output, with a standard specification of less than 10pC partial discharge at rated output voltage, with no external high voltage filtering required. As an option, all HV reactor may be supplied with a specification of less than 2pC partial discharge at rated output voltage, with no external high voltage filtering required.**

- **High voltage filtering techniques and shielded test rooms may be employed for testing where even less than 2pC must be measured.**

## *- Modular Cascade Cylinder Type HV Reactor*

- **In this design, the oil insulated high voltage reactor is mounted within a conducting cylinder, typically steel, which is suspended vertically between two insulating cylinders, typically fiberglass. The top and bottom of the module are capped with conducting header plates, typically steel, which often serve directly as the output terminations.**

- **The conducting cylinder, reactor core and drive frame are connected to an intermediate potential (1/2 of the rated output voltage of the module) within the conducting cylinder.**

- **Phenix Technologies Modular Cascade Cylinder Type HV Reactors may only be operated in series resonant mode.**

- **The HV output is normally taken from the corona rings or special output electrode (for voltages in excess of approximately 800 kV) which are bolted to the top plate. Since no bushing is involved, there are no voltage limitations imposed by the output termination.**

- **Modular Cascade Cylinder Type HV Reactors are normally designed to be stacked with the HV reactor windings connected electrically in series. This allows for theoretically unlimited maximum test voltages. Units with output voltages well in excess of 2 MV are currently in operation.**

- **Voltage measurement is usually accomplished via an external voltage divider capacitor, which may also serve as a the preload capacitor for series mode resonant operation. With the appropriate coupling coupling circuitry, this same capacitor may also be used for partial discharge measurement.**

- **Unless a preload capacitance is connected which is within the specified tuning range of the HV reactor, full voltage cannot be developed with no load capacitance present.**

- **Modular Cascade Cylinder Type HV Reactors may be supplied with paralleling bars, which may be installed to make various series / parallel connections among the modules. This provides the same effect as providing output taps, which allows for tuning over a greater capacitance range.**

- **A minimum 20 to 1 tuning range is typical for each output tap supplied.**

- **All Phenix Technologies HV reactors are specified to provide exceptionally clean high voltage output, with a standard specification of less than 10pC partial discharge at rated output voltage, with no external high voltage filtering required. As an option, all HV reactor may be supplied with a specification of less than 2pC partial discharge at rated output voltage, with no external high voltage filtering required.**

- **High voltage filtering techniques and shielded test rooms may be employed for testing where even less than 2pC must be measured.**

## Duty Cycle and Thermal Issues to be Considered in the Specification of an AC Resonant Test System

**- Tank Type HV Reactor**

- **Tank Type HV Reactors are better suited for continuous or long term duty operation if no external cooling system is to be provided.**

- **The steel tank design exhibits better heat dissipation characteristics than a fiberglass or plastic cylinder, which tends to limit heat transfer from the oil to the outside.**

- **To increase kVA capacity or duty cycle in a given physical size, additional cooling measures may be used to transfer heat away from the coils. Possible measures include:**

    1) **Use of radiators on the tank to increase the effective surface area of the tank for cooling purposes. This is the most economical and easily implemented solution. No customer action is required.**

    2) **Use of radiators on the tank in conjunction with fans outside the tank. This is also quite economical and easy to implement, and only requires the customer to supply AC power to the fans.**

- **Although more elaborate cooling systems involving heat exchangers can be used if more cooling is required, such measures are very seldom required for tank type HV reactors.**

- **Specification of actual duty cycle is extremely important. Proper specification of duty cycle will lead to an optimal solution for the customer in terms of cost, physical dimensions, and performance.**

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## - Modular Cascade Cylinder Type HV Reactors

- **Modular Cylinder Type HV Reactors are not generally suited for continuous or long term duty unless special provisions are made to provide additional cooling.**

- **Cooling for long term or continuous duty operation may be provided through simple addition of radiators to the center conducting cylinder of each reactor module to increase the effective surface area for cooling.**

- **For even higher kVA capacities and increased duty cycles up to and including continuous duty, the use of external cooling systems may be required. Possible measures include:**

  1) **Use of an oil-to-air heat exchanger external to the tank, to exhaust heat into free air. This is somewhat costly, and the customer must provide power to the oil pump(s), power to the fan(s) on the heat exchangers, and plumbing to carry the oil from the tank to the heat exchanger. Such measures are normally required only for systems designed to operate for extended periods of time.**

2) **Use of an oil-to-water heat exchanger external to the modules, to exhaust heat either into a continuous cool water supply or into a re-circulated water supply cooled by a chiller if a continuous cool water supply is unavailable. This is the most expensive and difficult to implement solution, as the customer must provide power to the oil pumps, plumbing for the cooling water, and either a continuous supply of cooling water or power to operate a chiller. This measure would normally only be required for a very large unit designed to operate at true continuous duty.**

- **Specification of actual duty cycle is extremely important. Proper specification of duty cycle will lead to an optimal solution for the customer in terms of cost, physical dimensions, and performance.**

# Determination of the Quality Factor "Q" In The Specification of an AC Resonant Test System

- Determination of the System "*Q*" is one of the most critical aspects of properly specifying a resonant test system, as the system "*Q*" directly impacts the size of the test system input service, isolation transformer (if required), test regulator, low voltage power line filters and exciter transformer.

- From theory, the Quality Factor "*Q*" of a resonant circuit may be mathematically expressed as the ratio of output reactive power to input real power. Or:

$$Q = \frac{kVAR_{out}}{kW_{in}}$$

- In a properly tuned resonant circuit, the reactive powers absorbed by the variable HV reactor and the test capacitance are equal and 180 degrees out of phase in time. This energy is transferred back and forth between the test object and the HV reactor at power frequency.

- The only power which must be supplied by an external source to maintain this resonant condition is the ohmic (real power) losses produced by power which is dissipated within the test circuit.

- The real power losses must be supplied by the input service to the test system via the isolation transformer (if required), regulator and exciter transformer. The required output power as well as the system "*Q*" must therefore be determined in advance to properly size the input power components.

- Losses in the resonant circuit are a result of HV reactor losses, and test load losses. These components are described in more detail as follows:

- **Reactor Losses: This represents the real power dissipated in the HV reactor itself at a given output voltage and current. This power loss results from resistive losses in the HV reactor windings, magnetic losses in the HV reactor core steel, and any other stray losses in the tank or frame structure.**

- **Test Load Losses: This represents the real power dissipated in the test object at a given voltage and current, which includes losses in insulation of the test specimen due to resistive leakage current, losses in any termination equipment used to make a corona free connection to the test object, and any other stray losses external to the HV reactor.**

- **The required Test Specimen Reactive Power may be calculated as:**

$$\text{Test Power} = \frac{V_{output}^2}{X_c} \; [kVAR]$$

**Where $X_c$ represents the capacitive reactance of the load, calculated as:**

$$X_c = \frac{1}{2\pi f C_{load}} \; [\Omega]$$

**Where $f$ represents the power frequency [Hz]**

**And $C_{load}$ represents the capacitance of the test object [F].**

- **System "*Q*" may then be calculated as:**

$$\text{System "}Q\text{"} = \frac{\text{Test Specimen Reactive Power}}{\text{Reactor Losses} + \text{Test Load Losses}}$$

- A system "$Q$" is usually calculated and specified at maximum rated output voltage and power, where system losses are the greatest.

- Typical system "$Q$" values for different types of test objects are given as follows:

| | | |
|---|---|---|
| - $SF_6$ insulated switchgear | : | 40 |
| - XLPE Cable (no water term.) | : | 40 |
| - PF Correction Caps. | : | 40 |
| - XLPE Cable / Water Terminations | : | 10 to 20 |
| - Generator Windings | : | 10 |

- Using similar logic, individual "$Q$" values may be calculated for the reactor ($Q_{reactor}$) and the test load ($Q_{load}$). In this case the system "$Q$" may be expressed as:

$$Q_{system} = \frac{Q_{reactor}}{1 + \dfrac{Q_{reactor}}{Q_{load}}}$$

## Mode of Operation: Series Resonant Mode vs. Parallel Resonant Mode

- **The decision on mode of operation, either series resonant or parallel resonant, is made according to the test object and the measurements to be carried out.**

- **In most cases, tests can be performed in either mode of operation, however certain type of testing are easier to perform in one mode than another.**

- **Since with Phenix Technologies resonant test equipment parallel mode operation is only possible with Grounded Tank Type Resonant Test Systems, the question of mode of operation should be addressed in the specification stage of an equipment purchase.**

***- Series Resonant Operation***

- **Series resonant operation is better suited for sensitive partial discharge measurements.**

- **Line noise from the power line is better suppressed in series mode operation. The series resonant circuit represents a low pass filter with a pole located at the resonant frequency, which in this case is the power frequency of 50 or 60 Hz.**

- **The energy released during specimen failure is considerably lower in series resonant mode operation than in parallel mode operation.**

- **Precise tuning is more difficult in series resonant operation than in parallel resonant operation, and voltage control is less stable. The series resonant operating point is extremely sensitive to small tuning changes.**

- **Operation at full output voltage is not possible in series resonant operation without a capacitive preload present at the output of the HV reactor.**

## *- Parallel Resonant Operation*

- **Parallel resonant operation provides a more stable output voltage for unstable test specimens such as large generator windings, or other test specimens with unstable ohmic component due to partial discharge or corona losses.**

- **In parallel resonant operation, the rate of rise of the test voltage is stable with the rate of rise of the regulator output.**

- **Tuning changes appear as current fluctuations at the regulator and exciter transformer, rather than voltage fluctuations at the output of the HV reactor.**

- **Parallel resonant operation permits operation at full voltage with no load present at the output of the HV reactor. This feature can be quite useful when type testing very short lengths of cable which require very little power.**

# Issues to Be Considered in the Specification of a HVDC Dielectric Test System

## - *Voltage Required*

- The maximum DC voltage required must be specified. This depends on the objects to be tested, and the test procedures of the customer. These procedures may be regulated by national or international standards for the objects under test.

- Some HVDC Test Systems are fixed in their output voltage capability, whereas others are offered as modular systems whose maximum voltage output is expandable via addition of more modules.

- At some point in the expansion of a modular HVDC Test System, increases in maximum system voltage will come at the expense of maximum output current, as the regulator and transformer(s) of lower stages must supply power to all subsequent stages.

***- Maximum Current Required***

- **Generally speaking, the maximum current required of any HVDC Test System is determined by two parameters:**

  **1) The sum of the resistive leakage current and any partial discharge current of the test object at maximum test voltage**

  **2) The amount of time allowed to reach the desired test voltage**

- **From theory, the test specimen current when performing HVDC tests is comprised of four components. These are:**

  **1) The capacitive charging current due to the application of direct voltage to the test specimen:**

  **This current represents electrical charge being transferred onto the test object. The charge transferred to the test object represents potential energy which is stored in the electric field of the test object's capacitance. It is this electric field which stresses the insulating material which is under test.**

2) **The dielectric absorption current due to slow charge displacements within the insulation of the test object:**

   **This component of current may persist for periods of a few seconds up to periods of several hours. It is this component of current which is of interest when doing polarization index tests on winding insulation in rotating electrical machines.**

3) **The continuous leakage current of the test object insulation at maximum test voltage, which is the steady state direct current which has to be supplied to maintain a constant direct voltage after components 1) and 2) have decayed to zero:**

   **Neglecting partial discharge losses, this current is the minimum current which must be supplied to the test object to reach and maintain the desired maximum test voltage. Theoretically, as long as at least this much current is available from the HVDC Test System, the test object can eventually be charged to maximum voltage.**

4) **Partial discharge currents due to partial breakdowns in the test object insulation, or corona losses in air due to inadequate conductor sizes or inadequate voltage clearances to other objects.**

- **Generally, all of the above components are small compared to component 1), the capacitive charging current. The amount of current required therefore normally reduces to a question of how much time can be allowed to charge a given test object to the desired test voltage.**

- **The amount of time required to charge an object may be approximately calculated, given the available charging current, the capacitance of the test object, and the desired test voltage to be attained. This is done as follows:**

**The total electrical charge *q* stored within a given capacitance at a given voltage *V* is expressed as:**

$$q = CV \text{ [coulombs]}$$

**Where: *C* = the test object capacitance [F]**
***V* = the desired test voltage [V]**

**1 ampere of current is defined as the flow of 1 coulomb of electrical charge past some reference point in a time interval of 1 second.**

**Hence the total amount of charge imparted to a test object with capacitance *C* in a time *t* may be expressed as:**

$$q = It \text{ [coulombs]}$$

**Where:** ***I*** **= the direct charging current applied to the test object [A] or [coulombs / second]**
***t*** **= the time for which the charging current *I* was applied [seconds]**

**The result, therefore, is:**

$$CV = It \text{ [coulombs]}$$

**Solving this for time:**

$$t = \frac{CV}{I} \text{ [seconds]}$$

**This relationship will provide an approximate amount of time required to charge a given test object C to a given voltage V, at a constant charge rate of I, with the following assumptions:**

1) **The charging current is maintained constant at I amperes, by an operator or automatic control system. In practice, the actual charging current may fall off a bit as the rated voltage of the HVDC Test System is approached, due to RC time constant limitations.**

2) **All other current components are small compared to the capacitive charging current of the test object. This is normally a good assumption.**

- **The following illustrative example shows how this equation may be applied to determine the amount of time required to charge a given capacitance to a given voltage at a given current.**

***Example:***

**Consider a reel of coaxial HV cable. The capacitance of the cable reel measured from the center conductor to the ground shield is 5 uF, and it is desired to charge the cable to 160 kVDC to withstand test the insulation. Assuming a 200 kV HVDC Test Supply is available, and is rated for 5 mA output current. Neglecting dielectric absorbtion, leakage and partial discharge losses, approximately how much time is required to charge the test object to the desired voltage?**

***Solution:***

**Using the relationship** $t = \frac{CV}{I}$ **[seconds] the approximate time is calculated:**

$$t = \frac{(5x10^{-6}\,\mathrm{F})(160{,}000\,\mathrm{V})}{0.005\,\mathrm{A}} = 160 \text{ seconds}$$

***- Duty Cycle Required***

- **Normally, continuous current capability is not required, as the charging current is only present for a few minutes or seconds.**

- **The time interval for which a HVDC Test System to rated to supply a given current essentially determines the maximum capacitance which can be steadily charged to rated test system voltage at that current. This does not mean that larger capacitances cannot be tested, but simply that they will have to be charged at a lower current for a longer time interval.**

- **When purchasing a standard HVDC Test System, calculations can be performed similar to those given in the previous example to determine if the system will meet the demands of particular test application.**

- **When purchasing a custom HVDC test system it is important to provide the equipment supplier with as much information as possible regarding the intended application of the system, to insure optimum performance.**

***- Polarity Required***

- **DC hipot tests may generally be performed using either polarity.**

- **Some HVDC Test Systems offer reversible polarity output. Others offer only a fixed polarity output, which is determined by the internal connection of the rectifier.**

- **The customer must determine based on their specific test requirements the required polarity, and this must be included in the specification for the specific test system.**

***- Measurements to Be Made***

- **If a HVDC test is simply a withstand voltage test, voltage may be the only critical measurement. Voltage measurement by resistive voltage divider is the normal method used for voltage measurement in most HVDC testing applications.**

- **If leakage current through the insulation of a test object must be measured, special guard / ground metering circuitry may be employed to differentiate leakage current returning from the grounded side of the specimen from output current measured at the return of the power supply.**

- **If percentage ripple is important, ripple detection circuitry can be included to monitor the ripple voltage and either illuminate an indicator if the percentage ripple increases above a preset limit, or display the percent ripple directly.**

***- Percentage Ripple Required***

- **Generally, unless a very high component of leakage current is present in a test object, the capacitance of the test object provides enough filtering effect to essentially eliminate ripple once a steady direct test voltage is reached.**

- **Depending on the type of HVDC rectifier circuit provided in the test system, the ripple may be quite high during the charging of a test object. Once the object reaches full test voltage the test object's own capacitance holds the voltage constant, dropping only the amount permitted by the natural RC discharge rate between successive voltage peaks coming from the test supply.**

- **For HVDC testing of largely capacitive test objects, even a single phase half wave rectifier is usually adequate to maintain a sufficiently low ripple at constant test voltages.**

- **For test objects with a larger resistive leakage component, additional measures may be taken to reduce the ripple voltage, such as the use of full wave single phase rectifier circuits, high voltage filtering capacitors, or 3, 6 or 12 pulse three phase rectifier circuits.**

- **Higher supply frequencies, supplied by solid state power supplies, are sometimes used when low ripple is required in the presence of a large resistive leakage component. The higher frequency allows the test object's own capacitance to provide better filtering performance, as well as a reduction in the size of additional filtering capacitors which may be used.**

## *- Type of Load*

- **In general, the type of load will determine the major characteristics of the required HVDC test system.**

- **Large capacitive loads with a small resistive leakage component will require no filtering for ripple reduction, but may require a high output current capacity for quick charge times.**

- **Loads with large resistive leakage may require special rectifier circuits and additional filtering to provide suitably low ripple output.**

- **Loads with a large resistive leakage component may need a higher duty cycle, since the leakage current remains constant as long as the voltage is applied. This is different than a large capacitive load with a small leakage component, where the charging current decreases with time.**

- **The type of load should be considered in the specification stage of an equipment purchase of an HVDC Test System to insure optimum performance for a given application.**