Improved Control of Field Current Heating for Voltage Stability Machine Design - Powerformer™

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Abstract: The risk for voltage collapse requires that the system operator use available reactive resources in the receiving area to maintain the voltage level. There is hence a need to boost the reactive generation from synchronous machines. ABB has developed a new class of synchronous machines, Powerformer™, which are able to deliver electric power directly at transmission voltage levels. The first Powerformer has a rating of 45 kV, 11 MVA and 600 rpm. It has now (October 200) accumulated more that 10 000 hours of successful operation. Powerformer has a better overload capability than a conventional generator.

I. INTRODUCTION

The risk for voltage collapse requires that the system operator use all available reactive resources in the receiving area to maintain the voltage level. There is hence a need to boost the reactive generation from synchronous machines in the receiving area and to use the field circuit up to its thermal limit. There is even a need to boost temporarily the field current beyond its steady state limit.

Several utilities have modernised steam turbines and nuclear reactor systems to generate more active (real) power. Turbine capacity is now sometimes so high that the armature current determines the amount of reactive power, which can be generated by the synchronous machine. During normal operation, the hot spot temperature of the rotor and the stator is usually lower than their steady state limits.

II. BACKGROUND

On 25 February 1988 ABB released the news that the company had developed a synchronous machine (Powerformer™) with a completely new HV armature winding. ALSTOM Power has acquired an exclusive license to market, sell, design and manufacture Powerformer. The new insulation system makes it possible to connect the machine directly to the HV network without any intervening step-up transformer, see Figure 1.

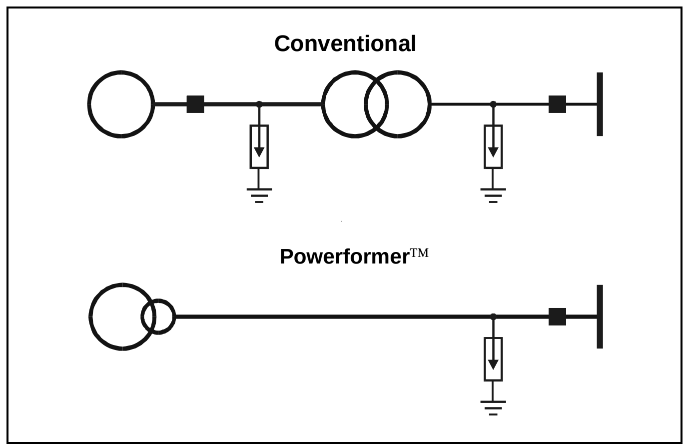

Figure 1 A conventional plant with step-up transformer and a plant with Powerformer.

It is well known that a rectangular conductor shape causes an uneven electric field distribution with critical concentrations at the corners of the conductors. This hampers the voltage from a conventional generator to reach levels higher than about 36 kV.

The winding in Powerformer consists of a cylindrical conductor with solid insulation. The new concept yields a smooth electric field distribution around the conductors, essential for a high-voltage electric machine, see Figure 2. The immediate consequence of the omission of the step-up transformer and thereby the elimination of the associated losses and costs as well as the opening up for new applications. Powerformer offers higher efficiency, 0.5-2%, than a conventional generating unit consisting of a synchronous machine, switchgear and a generator step-up transformer.

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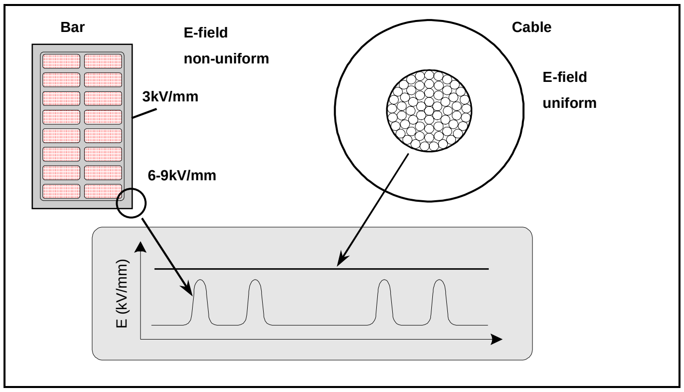

Figure 2 Illustration of the electrical field distribution in a cylindrical cable compared with a stator bar with rectangular shape.

III. DESIGN ASPECTS

The winding concept based on proven high-voltage cable technology enables a new type of high-voltage electric machine. Powerformer incorporates into one single unit, the functions of both the traditional generator and the transformer.

A. Cable design

Figure 3 shows the cable in Powerformer. The cable consists of a stranded conductor (1), an inner semiconducting layer (2), a solid dielectric (3) and an outer semiconducting layer (4).

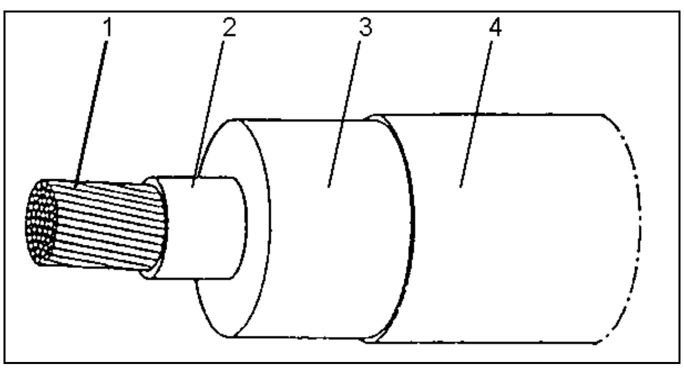

Figure 3 The cylindrical armature winding.

The solid dielectric is a cross-linked polyethylene (XLPE). There are neither metallic screens nor sheaths in the cable used for Powerformer. A conductor used in an electrical machine is exposed to a higher magnetic flux than a conductor used in power cables. In order to minimize the additional losses due to the magnetic leakage flux in the Powerformer conductors, it is necessary to subdivide the conductor into mutually insulated strands.

B. Electrical field control

The outer semiconducting layer is held at earth potential throughout the whole length of the cable winding. Consequently, the control of the electric field in the end region is much easier than in a conventional generator. This has a number of advantages. First, there is no risk for partial discharges or corona in any region of the winding. Second, the personal safety is increased substantially as the end-region is at ground potential.

C. Cooling system

The cooling system of the stator core in Powerformer is also based on a new concept. Most of the heat is generated in the stator core, which is held at ground potential. The new cooling system is an indirect system that cools the stator core by axially inserted water pipes. The water pipes are also made of cross-linked polyethylene (XLPE), virtually the same material as the cable insulation, except for that the water pipes use higher density XLPE.

One of the advantages with the axial cooling system without radial cooling ducts is that the stator core becomes homogeneous, which shortens the gross core length as well as improves efficiency. As the water-cooling is carried out at ground potential, there is no need for de-ionized water as in the conventional water-cooled stator windings. Hence ordinary tap water may be used for the cooling of the stator core of Powerformer. The use of plastic tubing also eliminates the risk for short-circuit between the tubes and the core and problems with eddy-currents in joints and pipes.

D. Temperature distribution

The maximum continuous conductor temperature in power cables with XLPE insulation is 90°C. Some users allocate an overload capability to cable systems. The overload operating temperature was originally set to 130ºC for cable systems. Now most users accept a temperature of 105ºC for XLPE, for short-term overload but some users specify a lower temperature for long-term overload.

The nominal operating temperature of the cable conductor in the present designs of Powerformer is below traditional XLPE cable operational temperatures. Compared to a conventional generator, of the same power rating, this value is exceptionally low. This conservative level is mainly selected due to the mechanical properties of XLPE.

IV. PORJUS

ALSTOM Power has installed the first Powerformer in Porjus hydropower plant, which is one of the hydropower plants along the Lule River in northern Sweden. The owner, Porjus Hydro Power Foundation, has refurbished the old hydropower plant in Porjus and created an advanced development, education and training centre.

This prototype machine, Porjus U9, is rated at 11 MVA, 45 kV, and 600 rpm. It is connected directly to a 45 kV bus bar without an intervening step-up transformer. U9 feeds its output power to the local 45 kV system and into the 130 kV regional network via the 130/45 kV transformer T13, see Figure 4. Porjus U9 has a secondary winding that can supply auxiliary power. The auxiliary winding has a rating of 110 kVA and 0.75 kV. This winding it is, in this case via a low voltage transformer, connected to the battery backed non-interruptible power supply (UPS) of the power station.

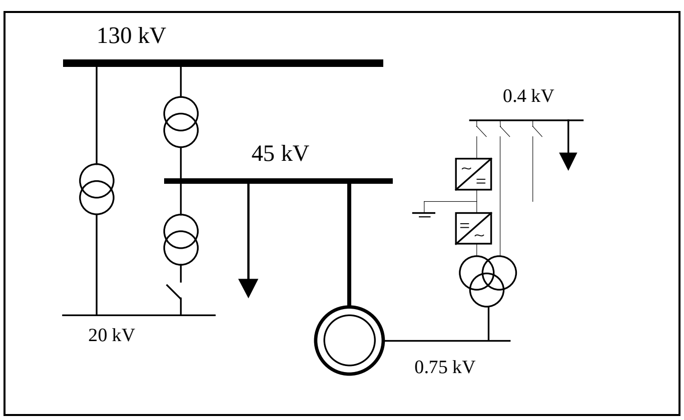

Figure 4 Single line diagram for the Porjus hydropower plant with Powerformer.

Porjus U9 has now (October 2000) accumulated more than 10 000 hours of successful operation. The unit has been synchronised to the grid more than 150 times and has hence been subjected to thermal and electrical cycling. Figure 5 shows the average active (real) power generation and during that latest 12 months and the accumulated operating time.

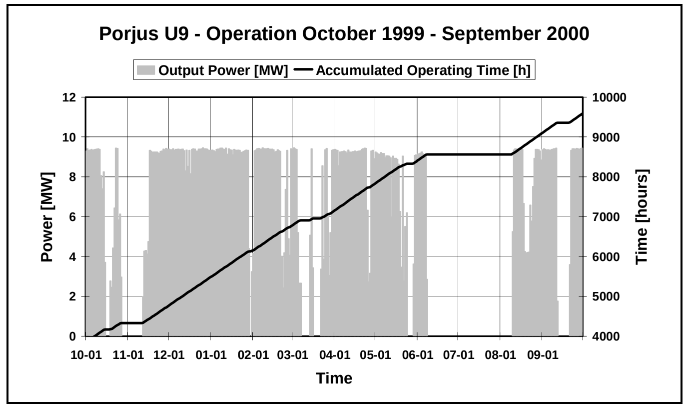

Figure 5 Power production and operating time in Porjus during the latest 12 months.

Figure 6 shows outages that have occurred after the first synchronisation on 31 May 1998.

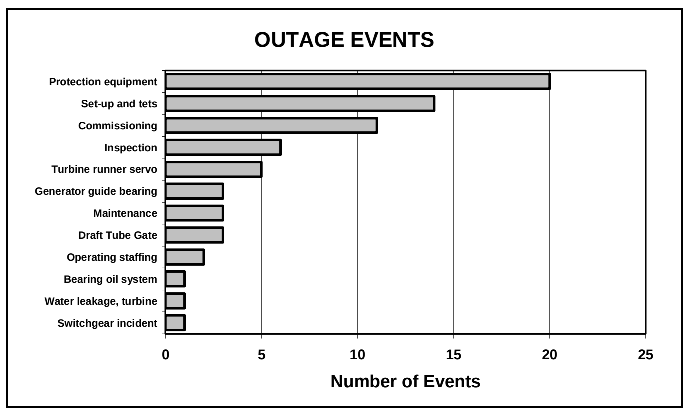

Figure 6 Breakdown of the outages.

V. ESKILSTUNA

In 1988 the Swedish utility Eskilstuna Energi & Miljö awarded ALSTOM Power a contract for the first Powerformer intended for thermal power applications. The machine has a rating of 136 kV, 42 MVA and 3000 rpm [4]. The generating unit will deliver its active (real) output power of 39 MW directly to an existing 136 kV switchgear located about 1.3 km from the plant.

The machine has undergone workshop tests and has successfully operated at 177 kV during overexcitation test. On 14 June 2000 Powerformer stood the sudden short circuit test from 100% of rated voltage. As expected, the currents at the test were close to 1000% of normal load current. This is the highest possible current, which may flow from Powerformer in case of faults in the transmission network.

The unit also performed well when subjected to a sudden single phase-to-earth fault on 15 June. In this case, the voltage on the two healthy phases temporarily exceeded 175% of normal operating voltage. This is the highest possible voltage, which may stress the insulation of the stator winding in case of faults in the cable connecting the Powerformer to the transmission network. Now (October 2000) the new CHP undergoes commissioning tests.

VI. PORSI

In 1998 Vattenfall, the largest electric power utility in Sweden, placed an order for a hydro Powerformer. It will replace one generator and one step-up transformer at the Porsi hydropower plant in northern Sweden. This machine will be rated 155 kV, 75 MVA, and 125 rpm. The commissioning of this Powerformer will commence late this year and commercial operation will commence early 2001.

VII. HÖLJEBRO

In June 2000 the Swedish utility StoraEnso Energy ordered the fourth Powerformer from ALSTOM Power. This machine will have a rating of 78 kV, 25 MVA and 115.4 rpm. It will be installed in Höljebro hydropower plant in central Sweden. This fourth Powerformer is scheduled to enter into commercial operation in June 2001.

VIII. DYNAMIC RATING

We will introduce the concept of *dynamic rating* that describes the allowable operating region of synchronous machines during transient conditions, such as power system emergencies like incipient voltage collapse. IEC defines three duty types for synchronous generators: (1) continuous running duty, (2) short-time running duty and (3) duty with discrete constant loads.

A. Continuous Running Duty

Most purchasers of generators specify *continuous running duty*. This means that the machine operates at a constant load maintained for sufficient time to allow the machine to reach thermal equilibrium.

B. Short-time Running Duty

Purchasers may also *specify short-time running duty*. This means operation at constant load for a given time, less than that required to reach thermal equilibrium, followed by a time at rest and de-energised, of sufficient duration to re-establish machine temperatures within 2 K of the coolant temperature. The duration of the load is so short that the machine does not reach thermal equilibrium.

C. Emergency Response Duty

During power system disturbances, such as loss of a generating unit, a transmission line, a power transformer or a busbar section, generators may have to carry higher load than rated load. The remaining generating units have to cover the load after a loss of a generating unit and after the loss of power import from neighbouring systems. Activation of the spinning reserve and depletion of the energy stored in the rotation masses covers the power demand. The system operator may then want to bring gas turbines on line to re-establish the spinning reserve an prepare for the next power system disturbance. The activation of a gas turbine may take from five to 15 minutes. There is a demand to use all synchronised power generating units during this interval. One way to boost the active power balance is to bypass pre-heaters in steam power plants. This creates a need for loading of generators above their rated load at continuous running. Gas turbines have a fairly high incremental cost and the system operator may want to replace them with less expensive generating units. There is a demand to maintain the load of synchronised units above the rated load at continuos running.

We conclude that the duty types defined by IEC do not reflect the demands on generating units during power system emergencies. A new duty type, *emergency response duty*, may better reflect the needs in connection with power system disturbances. During such emergency conditions the power utility may permit the conductor temperature to reach a higher value than that allowed at continuous running. During the first interval we allow such a high load that the temperature reaches the emergency temperature at the end of the interval. Then we have to reduce the load to prevent the temperature from rising above the emergency temperature. Figure 7 shows the emergency response of a machine.

The short-term emergency duration may vary from five to 20 minutes. Figure 7 depicts an emergency duration of 15 minutes, which is equal to the maximum response time of the fast disturbance reserve in the Nordel system. The long-term emergency duration may vary from two to four hours. Figure 7 depicts an emergency duration of four hours, which is equal to the maximum response time of the slow disturbance reserve in the Nordel system.

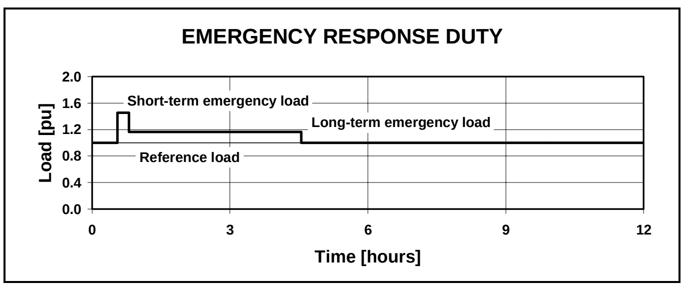

Figure 7 Load at emergency response.

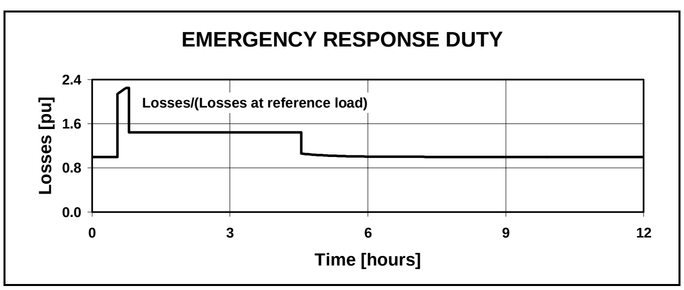

Figure 8 Losses at emergency response.

Figure 8 shows the conductor losses when the machine responds to a power system disturbance. We have used the conductor losses at reference load as a base for the losses.

We note that the losses are close to 200% of the losses at reference load. Figure 9 shows the temperature when the machine responds to a power system emergency.

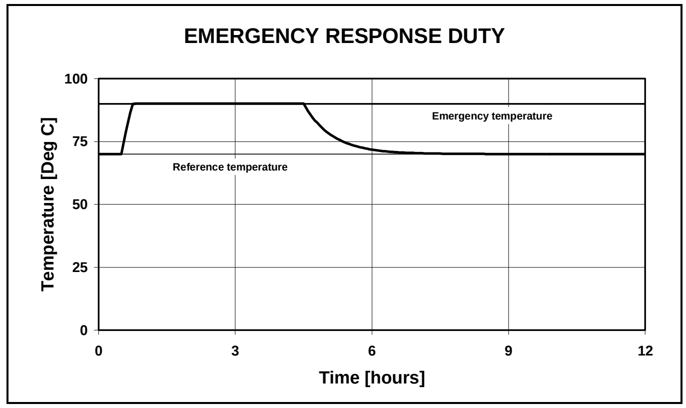

Figure 9 Temperature at emergency response.

We have selected the short-term emergency response load so that the conductor temperature reaches the emergency temperature after 15 minutes. We have selected the long-term emergency response load so that the machine has a thermal equilibrium at the emergency temperature. We have assumed that the emergency temperature is 90 degrees centigrade.

IX. A THERMAL MODEL

Consider a general conductor with uniform cross-section area as depicted in Figure 10. The conductor may represent the armature winding or the field winding in a synchronous machine. We assume that the conductor has a length, L [m] and a cross-sectional area, A, [m^2].

Figure 10 Adiabatic heating of conductor.

We also assume that the conductor carries an electrical current, I [A], which is initially equal to zero initially. Further, we assume that the current density is uniform, which means that we neglect the skin effect. Finally, we assume that the heating of the conductor is *adiabatic* and that the initial conductor temperature is equal to the ambient temperature (25°C).

Equation (1) below gives the resistance, R [Ω] of the conductor.

$$R = \rho_e \frac{L}{A} \tag{1}$$

Here:

ρ_e is the electrical resistivity of the conductor material [Ωm].

Equation (2) below gives the heating power, P_h [W] developed in the conductor.

$$P_h = R \cdot I^2 \tag{2}$$

The cooling power, P_c [W] is equal to zero because we have initially assumed that the process is *adiabatic*. Now, equation (3) below gives the conductor temperature, θ_c [°C].

$$m \cdot c_p \frac{d\theta_c}{dt} = L \cdot A \cdot \rho \cdot c_p \frac{d\theta_c}{dt} = P_h = \rho_e \frac{L}{A} I^2 \tag{3}$$

Here:

ρ is the density of the conductor material [kg/m^3],

c_p is the specific heat at constant pressure [J/(°C·kg)]

We simplify equation (3) and obtain:

$$\frac{d\theta_c}{dt} = \frac{\rho_e}{\rho \cdot c_p}\left(\frac{I}{A}\right)^2 = \left(\frac{S}{S_1}\right)^2 \tag{4}$$

Equation below (5) defines the *short-time current density*, S_1 [A/m^2].

$$S_1 = \sqrt{\frac{\rho \cdot c_p}{\rho_e}} \tag{5}$$

For a *copper* conductor we have: ρ =8930 kg/m^3, c_p =390 J/(°C kg) and ρ_e =1.75·10^{-8} Ωm and obtain:

$$S_{1,Cu} = \sqrt{\frac{\rho \cdot c_p}{\rho_e}} = \sqrt{\frac{8930 \cdot 390}{1.75 \cdot 10^{-8}}} = 14.1 \cdot 10^6 \quad \text{A/m}^2 \quad \text{or} \tag{6}$$

$$S_{1,Cu} = 14.1 \quad \text{A/mm}^2$$

Above we neglected that the electrical resistivity of the conductor material increases when the temperature increases. Equation (7) below gives, following IEC, the resistance, R_1 [Ω] at a temperature θ_1 [ºC] when we know the resistance, R_0 [Ω] at the temperature θ_0 [ºC]:

$$R_1 = R_0 \frac{\theta_1 + k}{\theta_0 + k} \tag{7}$$

Here:

k is the reciprocal of the temperature coefficient of resistance of the conductor material at 0 degrees centigrade.

For copper k = 235 [ºC].

Equation (8) below gives the conductor temperature when we take into account that the resistance of the conductor increases with temperature:

$$\frac{d\theta_c}{dt} = \frac{\theta_c + k}{\theta_0 + k} \cdot \left(\frac{S}{S_1}\right)^2 \tag{8}$$

The process of heating conductors in electrical machines is not adiabatic. There will be a cooling effect when the temperature of the conductor in-creases above the ambient temperature. Here we make the assumption that the cooling power is proportional to the difference between the conductor temperature and the ambient temperature. We also assume that the cooling power is equal to the heating power when the current density is equal to the rated current density of the conductor. This means that the conductor reaches thermal equilibrium at rated current density. We say that the rated temperature is equal to the equilibrium temperature at rated current density.

Figure 11 shows the temperature of a copper conductor when we consider both heating and cooling.

The time constant is close to 40 minutes for a conductor with a rated current density of 2 A/mm^2 and a rated temperature of 70 degrees centigrade. The time constant in this example is about 13 minutes for a conductor with a rated current density of 5 A/mm^2 and a rated temperature of 120 degrees centigrade.

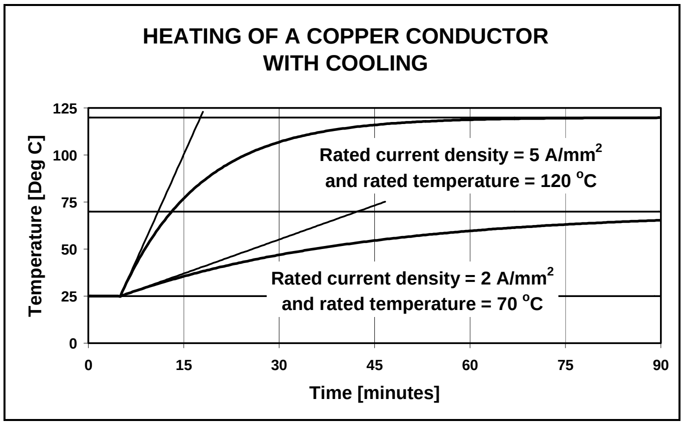

Figure 11 Heating of a conductor with cooling.

X. THERMAL RESPONSE

Powerformer has a lower armature current density than a conventional generator and a larger thermal mass. This means that there is a large potential in the thermal overload capability.

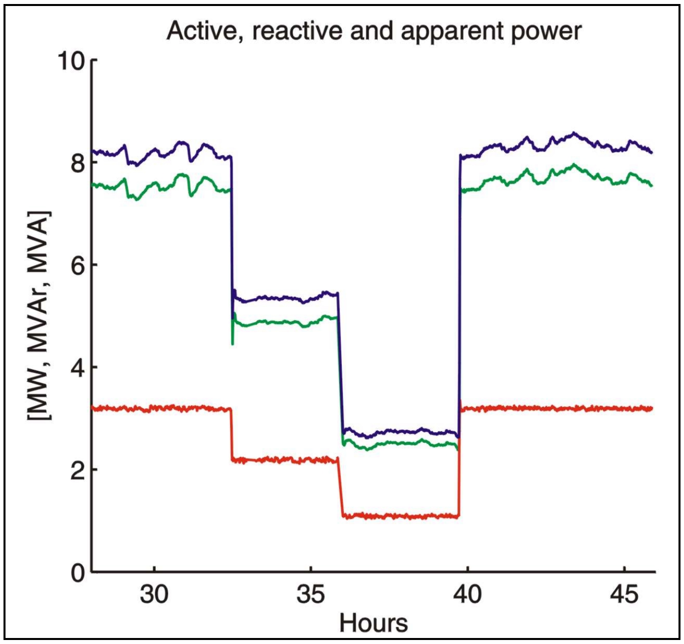

Figure 12 The used load cycle during the thermal time constant tests.

To evaluate the temperature response of the stator cyclic heat tests were performed. Figure 12 shows a production cycle of 75%-50%-25%-75% loading of the generator.

The corresponding maximum armature temperature for this load cycle is shown in Figure 13. Time constants for the three curves are between 80 and 130 minutes. The rotor winding time constant is in the range 13 to 20 minutes and differs only slightly from conventional generators. Note however that the rotor winding temperature is only around 80 degrees at rated conditions.

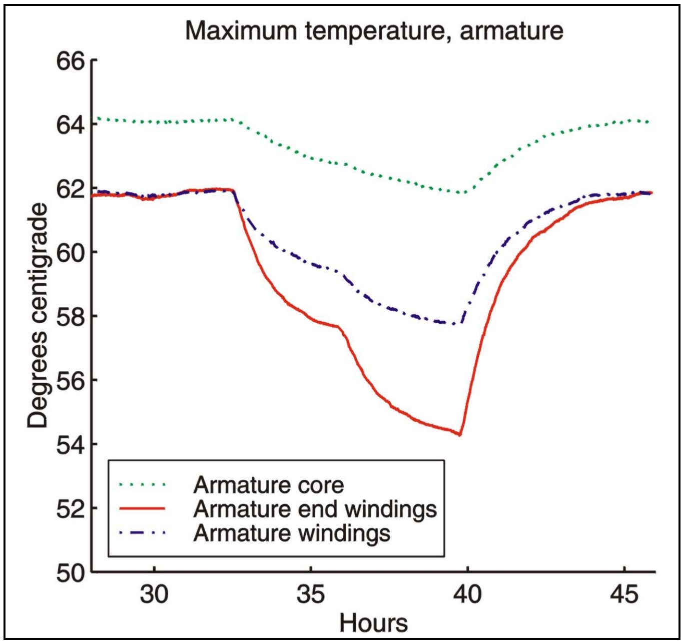

Figure 13 Armature core temperature (dotted line), Armature end winding temperature (solid line) and Armature winding temperature.

XI. CONCLUSIONS

We have shown that the time constant of Powerformer is longer than the time constant of a conventional generator. This means that the armature winding of Powerformer has a higher temporary overload capability than a conventional generator.

There is a need to define an emergency response duty to represent the requirements during power system emergencies. The extended capability diagram in Figure 14 is a simplified way of describing the emergency response of a synchronous machine. There is also a nee for a control system that can fully utilise the thermal capability of the machine.

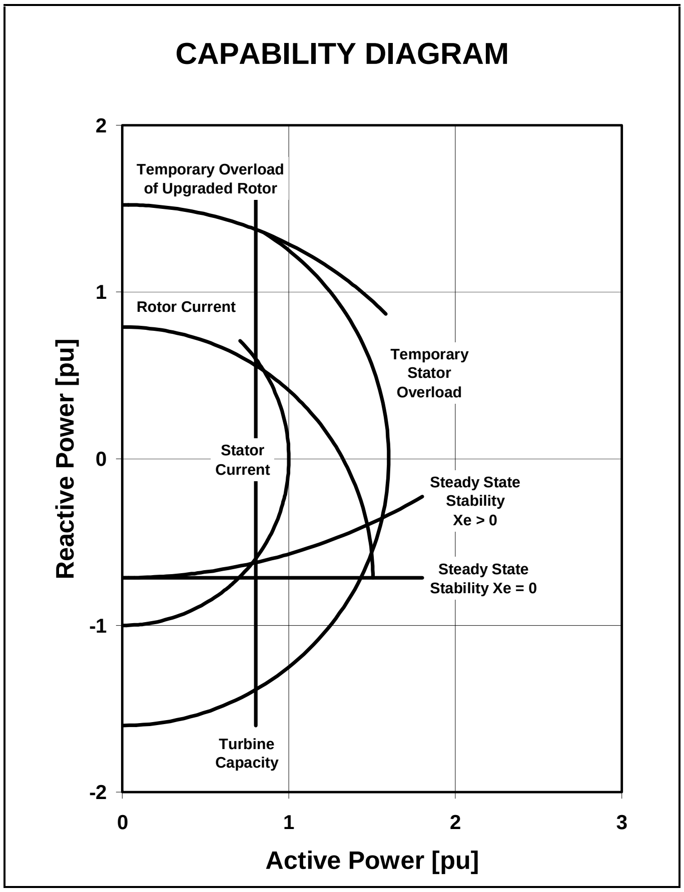

Figure 14 Extended capability diagram.

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XIII. BIOGRAPHY

Sture Lindahl joined ABB Generation in 1998, where he specialises in interaction between Powerformer and the rest of the power system. He obtained a Licentiate of Technology in Automatic Control and Measurement Methods from Lund Institute of Technology in 1972. Since then, he has worked for Swedish State Power Board, the Swedish utility Sydkraft, and ABB Relays in areas including transient phenomena, power system analysis, and marketing of protection equipment. n 1998, Chalmers University of Technology conferred the degree of Honorary Doctor on him. He is also adjunct professor in Electric Power Systems at Lund University of Technology.