CONSTRUCTION OF GENERATOR CAPABILITY CURVES

USING THE NEW METHOD FOR DETERMINATION OF POTIER REACTANCE

M.M. Kostić*, M. Ivanović*, B. Kostić*, S. Ilić** and D. Ćirić**

Electrical Engineering Institute Nikola Tesla, Belgrade, SERBIA*
TPPs-OCMs "Kostolac", Kostolac, SERBIA **

Abstract

- The capability (*P-Q*) curve of generator can be determined only on the base of examinations in the power plant, i.e. on the base of:
  - the no-load test, i. e. $i_{fl}(e_l)$ dependence, and
  - the reactive load test, i.e. characteristic points $A_i\,(i_f$, u)
- The Potier reactance (X_P) for the 3-4 points of the relevant values of reactive loads are determined, and then

  the capability (P_G-Q_G) curve of the generator is being constructed.
- This method is verified for experimental regimes of active and reactive power around the nominal values, on the example of turbo generator 348 MW in power plant "Kostolac B".
- The significant deviation in relation to the *P-Q* curve of the drive manufacturer's documentation generator were established, and

  it is recommended to update *P-Q* curves every 5-6 years or after major repairs.
- Similar deviations of *P-Q* curves were observed during the extensive testing and research for newer generators in U.S.

Introduction

- Capability curves, P_G-Q_G curves, Figure 1, are necessary to the operating stuff.
- The most important part of the curve is the part with coordinates ($Q_G \geq Q_{G,N}$, $P_G \leq P_{G,N}$) which defines the generator regime with increased reactive power.
- Significant deviations of capability curves, compared to manufacturers', were obtained during the extensive testing and research for generators in U.S. (Figure 1).

Introduction

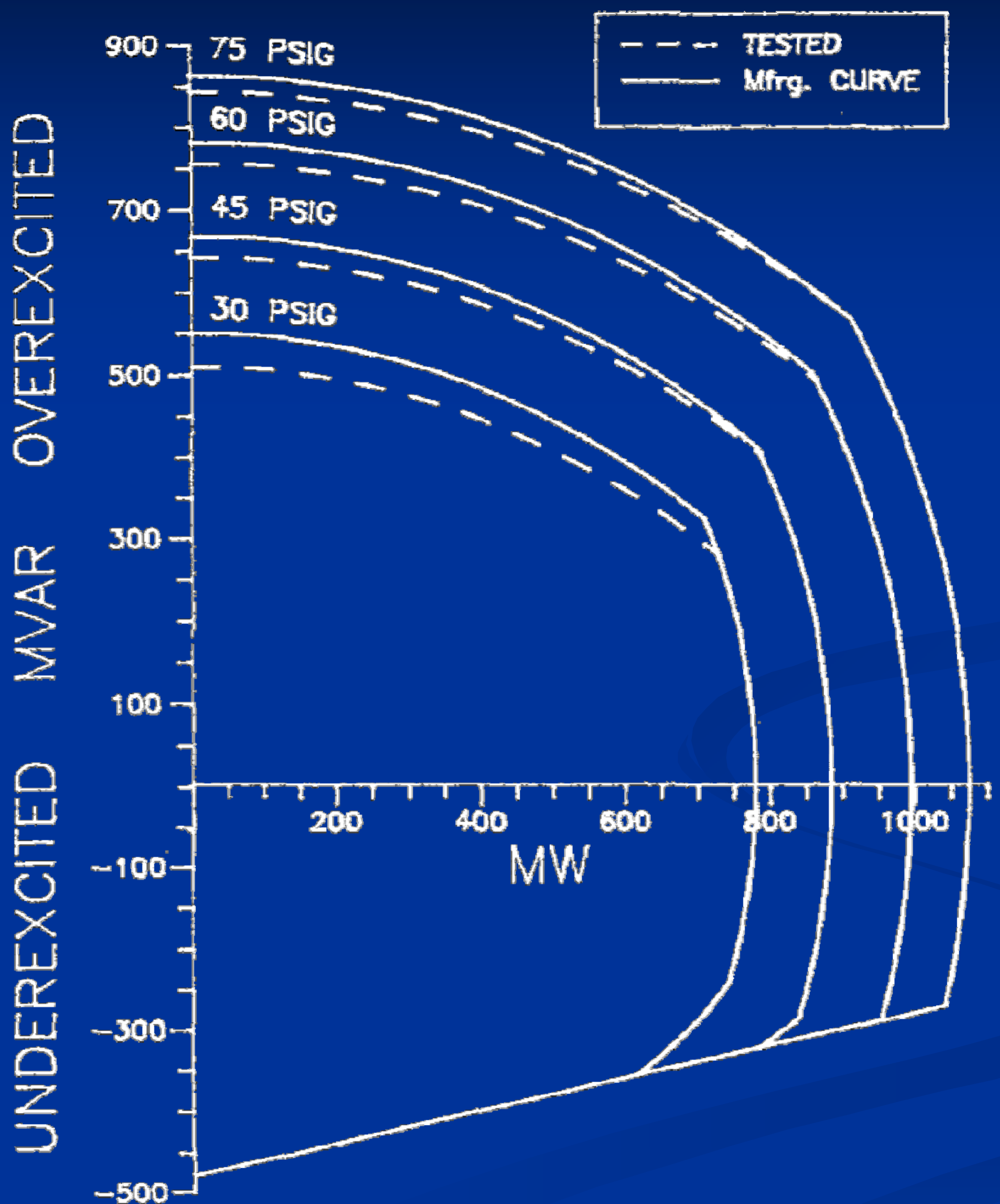


Figure 1: Comparison chart of actual capability (P-Q) curves with the manufacturers' generator capability curves

BASIC PRINCIPLES FOR THE DESIGN OF CAPABILITY CURVE

- Capability curve of generator with **unsaturated magnetic circuit**

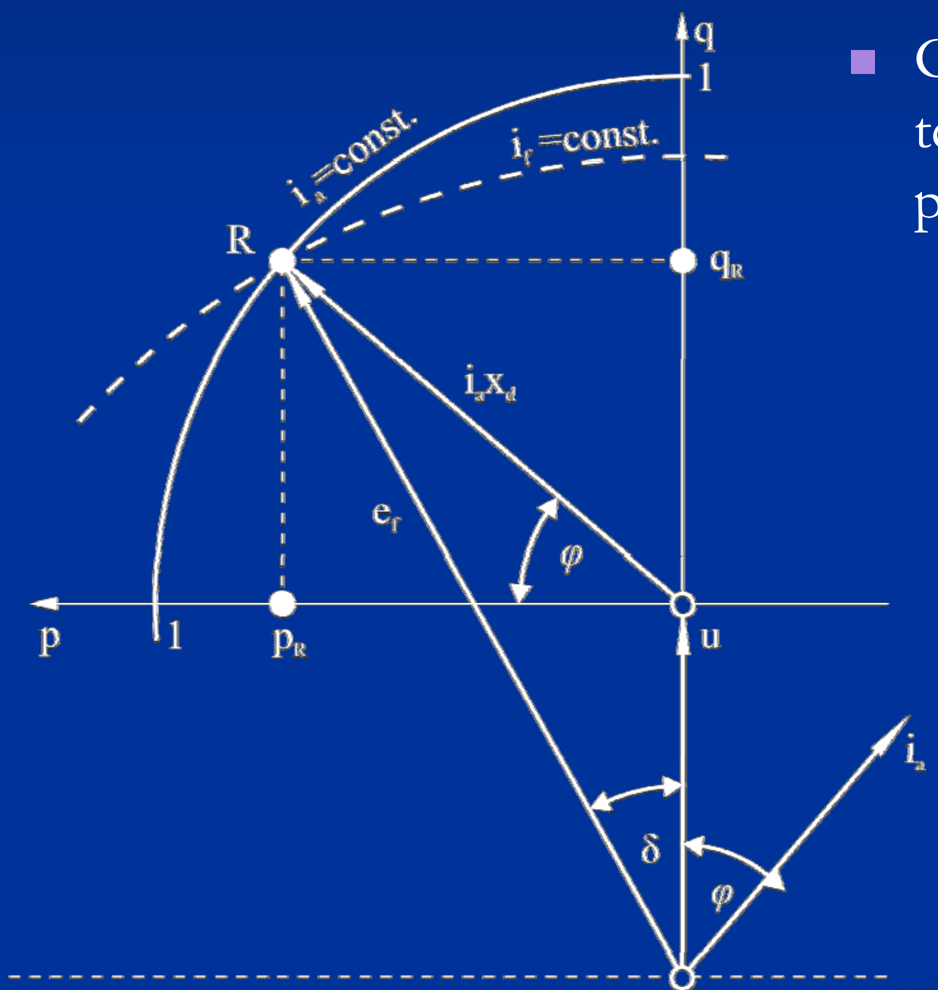


Figure 2: Vector diagram of generator electromotive forces and the excitation currents (with corresponding scaling ratio)

- Generator is sized to reach the nominal temperature at the rated values of (p_n) and (q_n) powers (the point R) i.e.:
  - for induct currents, $i_a = i_{an} = Const.$, $\varphi \le \varphi_n$, and
  - curve $i_f = Const.$ and $\varphi > \varphi_n$, i.e., $q \ge q_R$, with a reduced active power $p \le p_R$

BASIC PRINCIPLES FOR THE DESIGN OF CAPABILITY CURVE

- Vector diagrams of excitation currents of saturated machine
  - The curve of saturated machine, derived from no-load test, $\mathbf{i_{f0}(e)}$
  - It is particularly difficult to quantify additional magnetic saturation on the part of the rotor of loaded machine, i.e. $\mathbf{i_{fl} = f(e_l)}$.
  - Influence of additional saturation of the rotor magnetic circuit is taken into account by introduction of Potier reactance ($\mathbf{x_P > x_l}$, $x_{l\ is}$ stator leakage reactance) which results in increased EMF ($e_P = u+x_P \cdot i > u+x_l\, i = e_l$).

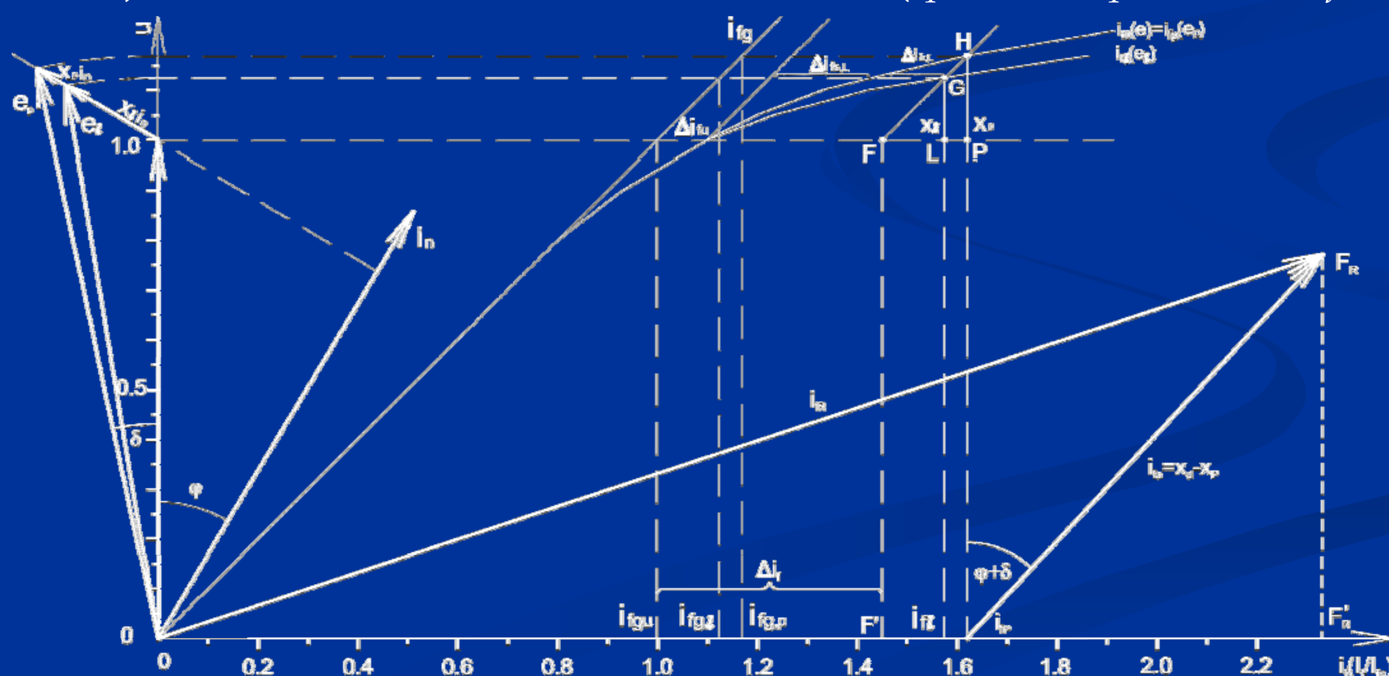
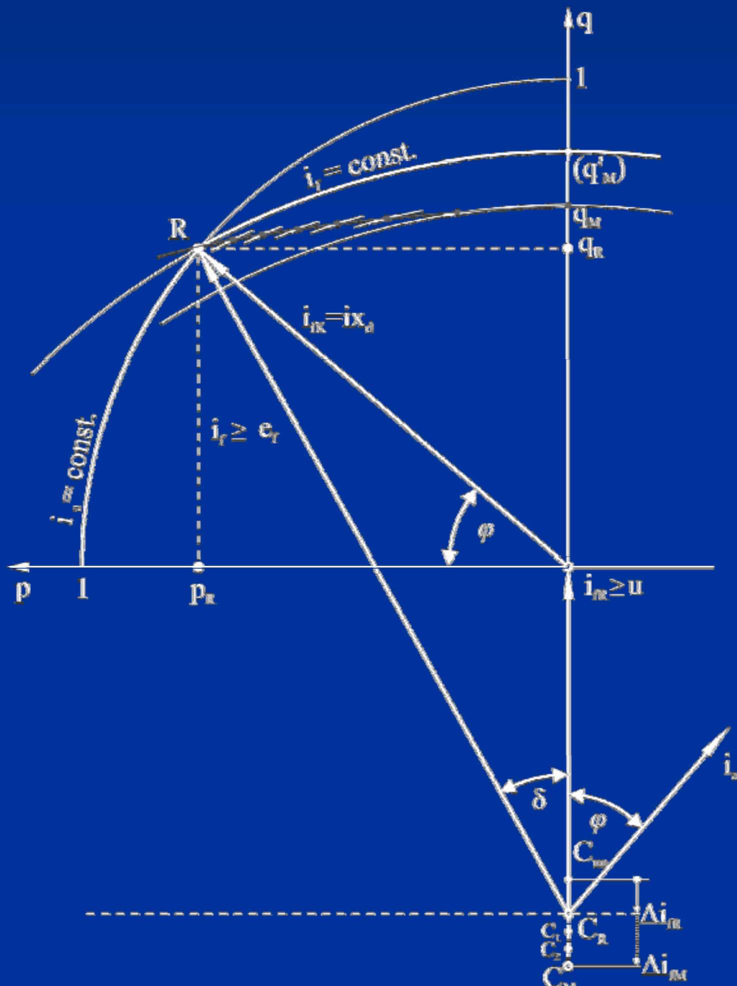


Figure 3: Magnetization curves $i_{f0}(e)$ and $i_{fl}(e_l)$; diagrams of excitation currents: $i_{fa,n} = x_d - x_P$ and $\mathbf{i_{fR}=i_{fP}+i_{fa,n}}$

BASIC PRINCIPLES FOR THE DESIGN OF CAPABILITY CURVE

- Capability curve of generator with **saturated magnetic circuit**



- The increase part of saturation current
  - $\Delta i_f\ (e_P) = \Delta i_{fu} + \Delta i_{fs} + \Delta i_{fr}$ (Figure 3)
  - beginning point C_{uns} goes down for $\Delta i_f(e_P)$ (C_R,C_1,C_2 and C_M)
  - the corresponding arches $i_{fi} = Const.$ are moved down as well.
- Thus, for pure reactive load ($p = 0$),
  - instead of point q'_M, point $q_M < q'_M$ is obtained
  - q'_M - reactive load maximum for generator with saturated magnetic circuit.

Figure 4: Diagrams of electromotive forces and excitation currents for generator with saturated magnetic circuit

DETERMINATION OF GENERATORS POTIER REACTANCE

- Potier reactance is not constant in given range of voltage and load.
- It is necessary to determine the Potier reactance dependence $x_P(u,q)$:
  - for accurate calculations and
  - capability curve construction.
- Determination of Potier reactance for **relevant (reactive) loads**:

$\boldsymbol{x_p}(P_{Gi}, Q_{Gi}) \approx \boldsymbol{x_p}(Q_{G,cos\varphi=0})$, for $Q_{Gi} = Q_{G,cos\varphi=0}$

since

$\boldsymbol{U_G}(P_{Gi}, Q_{Gi}) \approx \boldsymbol{U_G}(Q_{G,cos\varphi=0})$, for $Q_{Gi} = Q_{G,cos\varphi=0}$

and

$x_p = f(Q_G, U_G) \approx f(Q_G)$

For rated regime (P_{Gn}, Q_{Gn}, U_n):

$x_{P,n} \approx x'_{P90}$, for $i_{90}' = i_{an} \cdot sin\varphi_n$ .... (1)

In general case (P_G, Q_G, U):

$x_P \approx x'_{P90}$, for $i_{90}' = i_a \cdot sin\varphi$ ....
(2)

DETERMINATION OF GENERATORS POTIER REACTANCE

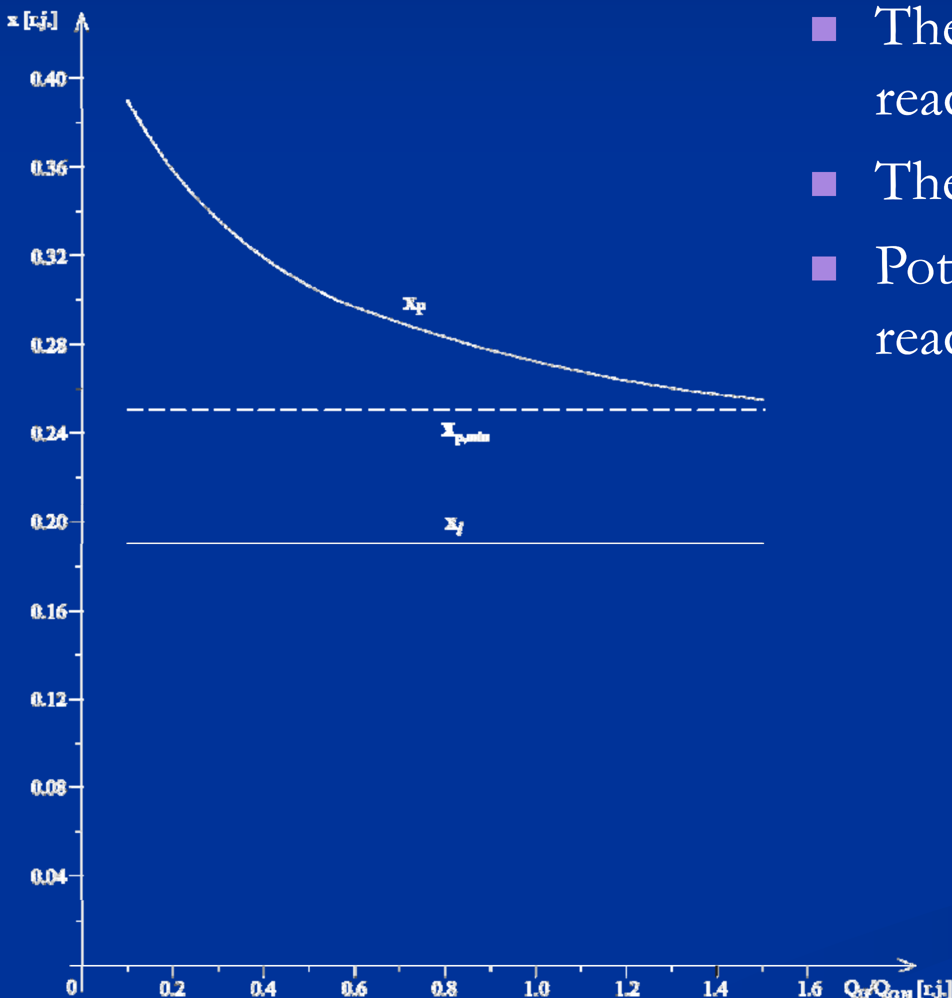
- The obtained values (dependences) of Potier reactance $x_p = f(Q_G, U_G) \approx f(Q_{G,cos\varphi=0})$ should be used for design of generator capability curve.
- The specified rule was verified on the example of generator GTHW360 (360 MW) for regimes around the nominal ($P_G \approx P_{Gn}$ and $Q_G \approx Q_{Gn}$), i.e. by comparison of:
  - measured values ($I_{f,meas}$), and
  - calculated values ($I_{f,calc}$), on the basis of Potier reactances (x_P) for $Q_{G,cos\varphi=0} \approx Q_{Gn}$.

  And, it is obtained

  $$\boldsymbol{I_{f,calc} = I_{f,meas} \pm 0.4\%}$$

DETERMINATION OF GENERATORS POTIER REACTANCE

- In Figure 5 is given a dependence of Potier reactance, $x_{p,i}$ (Q_G), for generator GTH-360



- The Potier reactance (x_p), is changing when reactive power changes.
- These values decrease with increase in load, but
- Potier reactance value is greater then leakage reactance, $x_{p,min} \approx 1.1 \div 1.15\ x_l$

Figure 5: Dependence of Potier reactance from reactive power, $x_{p,i}$($x_{p,i}(Q_G)$, and $x_l = 0.188 > x_{p,min}$

CONSTRUCTION OF GENERATOR CAPABILITY CURVE

- Determination of *P-Q* curve by a new method
  - The values of excitation current (I_f) can be calculated using the following expression (which is derived from a triangle OF_RF_R', Figure 3):

$$i_{fR} = \sqrt{\left[i_{fP} + (x_d - x_P)(s/u)(\sin\varphi\cos\partial + \cos\varphi\sin\partial)\right]^2 + \left[(x_d - x_P)\cdot(\cos\varphi\cos\partial - \sin\varphi\sin\partial)\right]^2}$$

  - For given (nominal) value of excitation current ($i_{fn} = i_{fR} = Const.$)
    - Corresponding values of active power (P_{Gi}) are calculated,
    - the independent variable takes the value of reactive load $Q_{Gi} \equiv Q_{Gi,cos\varphi \approx 0}$.
  - For a given value of excitation current $I_{f1,max}$ = 2550A:
    - the series of given values of reactive and active power were obtained,
    - the corresponding P-Q dependence is obtained (Figure 6).

CONSTRUCTION OF GENERATOR CAPABILITY CURVE

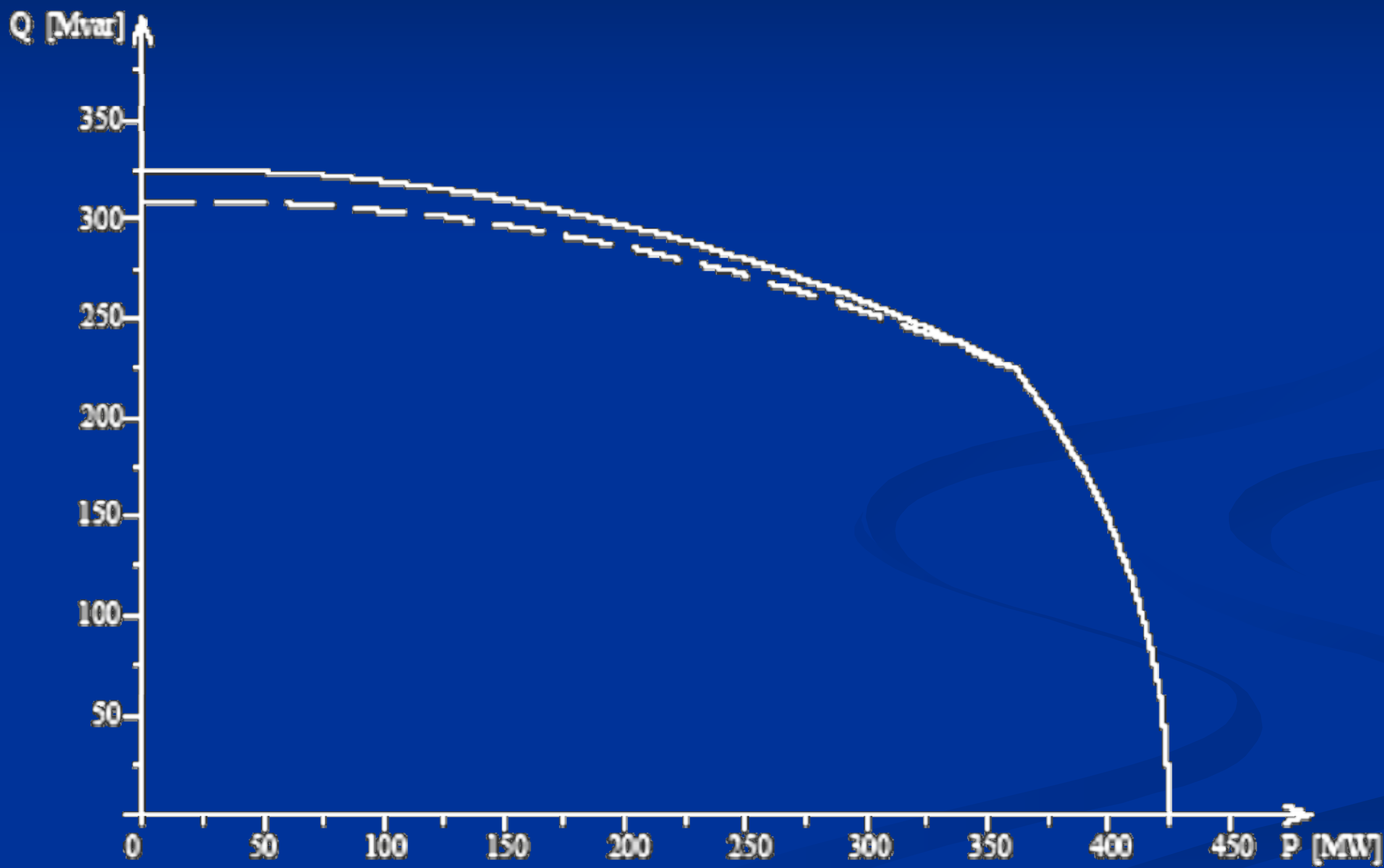


Figure 6: Capability diagrams for generator GTHW-360: curve from manufacturer's documentation (-) significantly deviates from the curve obtained during tests (- - -)

Conclusion

- It has been established that manufacturers' P-Q curve for generator GTH 360 gives **overestimated reactive power values** by 2%, 4% and 6%, for reduced active power: 250MW(0.71$P_{G,N}$), 200MW(0.581$P_{G,N}$) and 50MW, respectively.
- Similar deviations were observed during the extensive testing and research for newer generators in the U.S.
- Therefore, it is recommended to update *P-Q* curves every 5-6 years or after major repairs.

PROPOSAL FOR ADDITION OF IEC 34-4 STANDARD IN PART FOR DETERMINATION OF POTIER REACTANCE

M.M. Kostić*

Electrical Engineering Institute Nikola Tesla, Belgrade, SERBIA*

Abstract

The author came to the following conclusion:

- The Potier reactance value depends almost on turbo generator reactive current ($i_{aQ} = i_{an} \cdot sin\varphi$),

- This rule is proved by:
  - general qualitative analysis, and
  - experiment

- Thus, the addition of corresponding standard IEC 34-4/1985: ROTATION ELECTRICAL MACHINES is proposed, i.e. it is proposed that the Potier reactance should be determined from reactive load test:
  - for the excitation current which corresponds to the rated voltage and armature current value $i'_{a,cos\varphi=0} = i_{an} \cdot sin\varphi_n$, and
  - two additional values of reactive load $i'_{a,\, cos\varphi=0} > i_{an} \cdot sin\varphi_n$, which are convenient for construction of turbo generator capability (P-Q) curve, for the segment where $Q > Q_n$.

Introduction

- The armature leakage reactance is usually approximated by the Potier reactance.

- The values of the Potier reactance is greater than the leakage reactance (up to 50% of the leakage reactance, which is confirmed by the results of our research).

- The importance of Potier reactance determination is reflected in:
  - Leakage reactance is nearly independent on saturation ($X_\ell = Const.$).
  - Saturation curve of the generator under load conditions is assumed to be the same as the open-circuit saturation curve.
  - Any error introduced by the use of the open-circuit saturation curve is compensated by using the Potier reactance ($X_p > X_\ell$).
  - For turbogenerator, the air gap is assumed to be uniform so that
    - the direct-axis reactance is equal to the quadrature axis reactance, $X_d = X_q$
    - the unsaturated direct-axis reactance is calculated by equation $X_{du} = X_a + X_\ell$.

- In numerous researches it is shown that Potier reactance values depend on terminal voltage.

THE POTIER REACTANCE DEPENDENCE ON (REACTIVE) LOADS

- Based on research results, author came to the following conclusion:
  - The Potier reactance mostly depends on reactive currents ($i_{aQ} = i_{an} \cdot sin\varphi$),
  - It is verified by:
    - general qualitative analysis, and
    - experiment, for loads about rated active and reactive power, for generator GTHW 360 (360 MW)

- Standard procedure for determining Potier reactance is based on reactive load test with voltage and current which differ from their rated values by not more then ± 0.15 per unit.

- Author proposes that Potier reactance should be determined from reactive load test for three values of armature current:
  - $I_{a1}=I_{a,max}>I_{aN} \cdot sin\varphi_N$ (i.e. $Q_{G1}=Q_{Gmax}>Q_{GN}$), corresponding to $I_f=I_{f,N}$ and $U_{G1}= U_G$ at $Q_{G1}=Q_{Gmax}>Q_{GN}$ (point C_1, Figure 1);
  - $I_{a2}=I_{aN} \cdot sin\varphi_N$ (i.e. $Q_{G2}=Q_{GN}$) and $U_{G2}=U_G$ at $Q_2=Q_N$ (point C_3, Figure 1);
  - $I_{a3}=(I_{a1}+I_{a2})/2$, i.e. $Q_{G3}=(Q_{Gmax}+Q_{GN})/2$ and $U_{G3}=U_G$ at Q_{G3} point C_2, Figure 1).

DETERMINATION OF POTIER REACTANCE (STANDARD PROCEDURE)

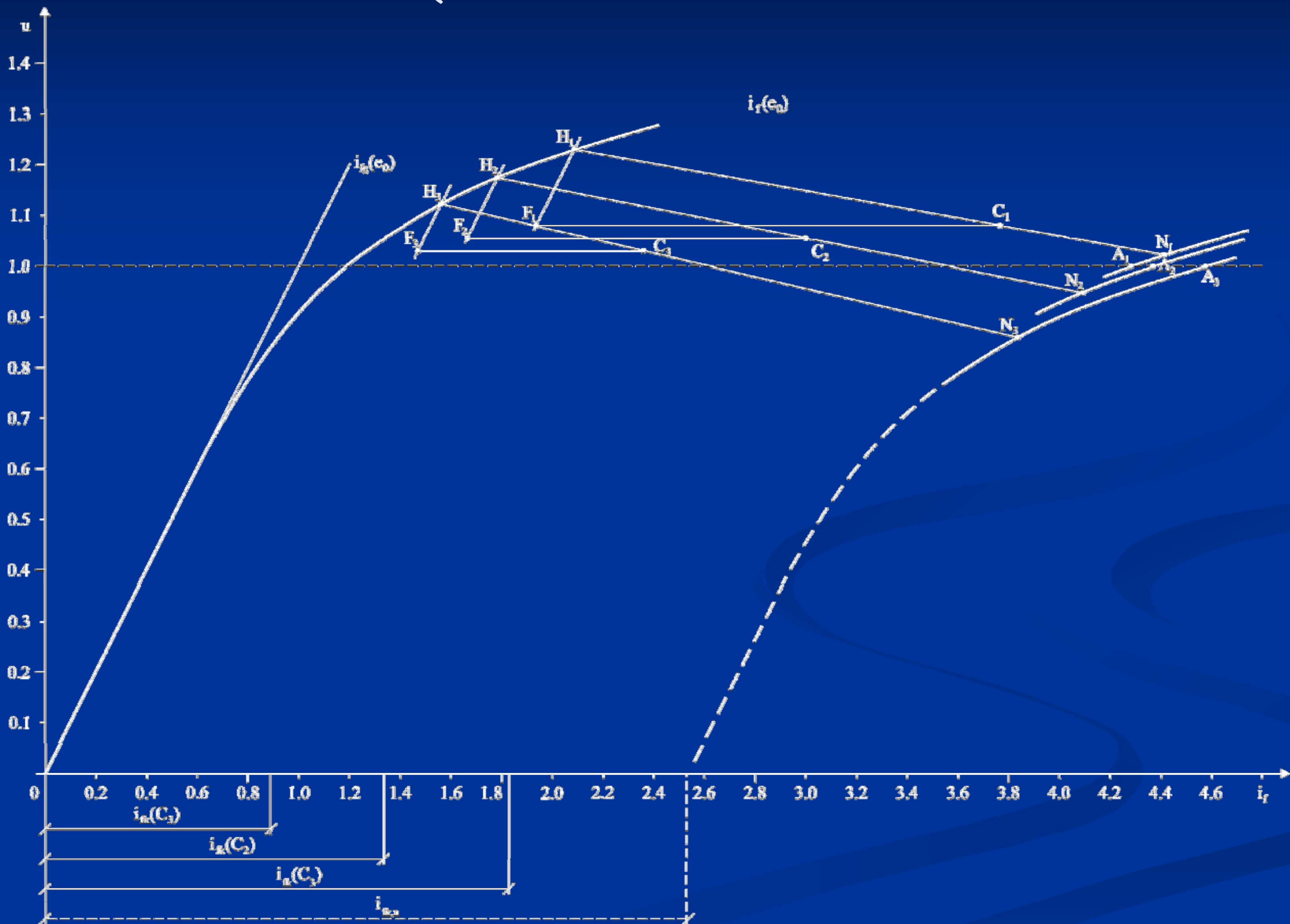


Figure 1: Determination of the excitation current at zero power-factor for three experimental points $i_1(C_1) > i_2(C_2) > i_3(C_3)$, and corresponding (accessory) points A_1, A_2 and A_3

DETERMINATION OF POTIER REACTANCE (STANDARD PROCEDURE)

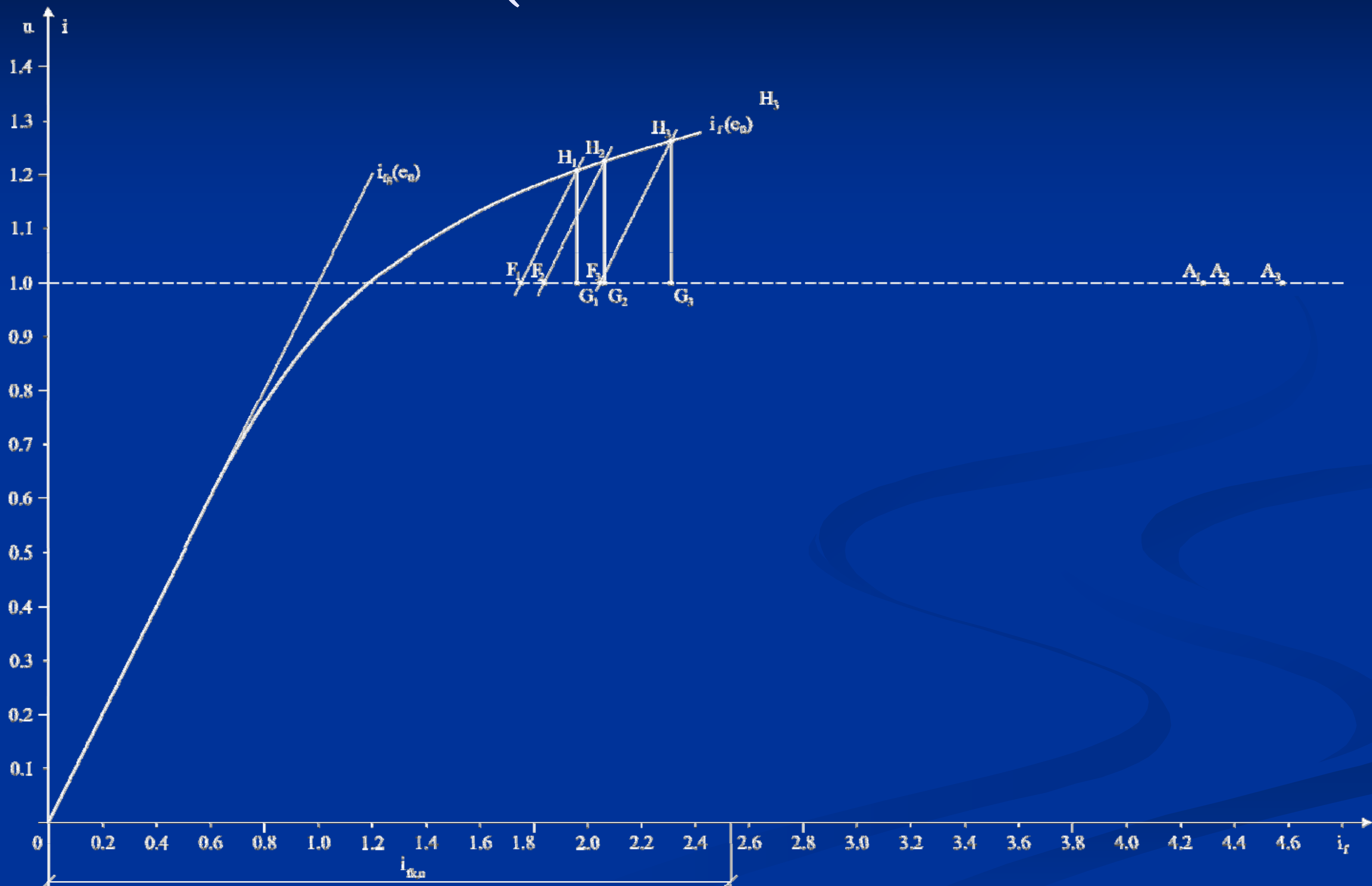


Fig. 2: Potier reactance, for three different exitation current at zero power-factor,

$X_P(A_3(C_3) > X_P(A_2(C_2)) > X_P(A_1(C_1)$, *for* $i_a(C_3) < i_a(C_2) < i_a(C_1)$

Potier reactance dependence on the load and the new method for its determination

- Reactances x_{Pn} and $x_{Pn,90}$ are determined using new method (Figure 3)

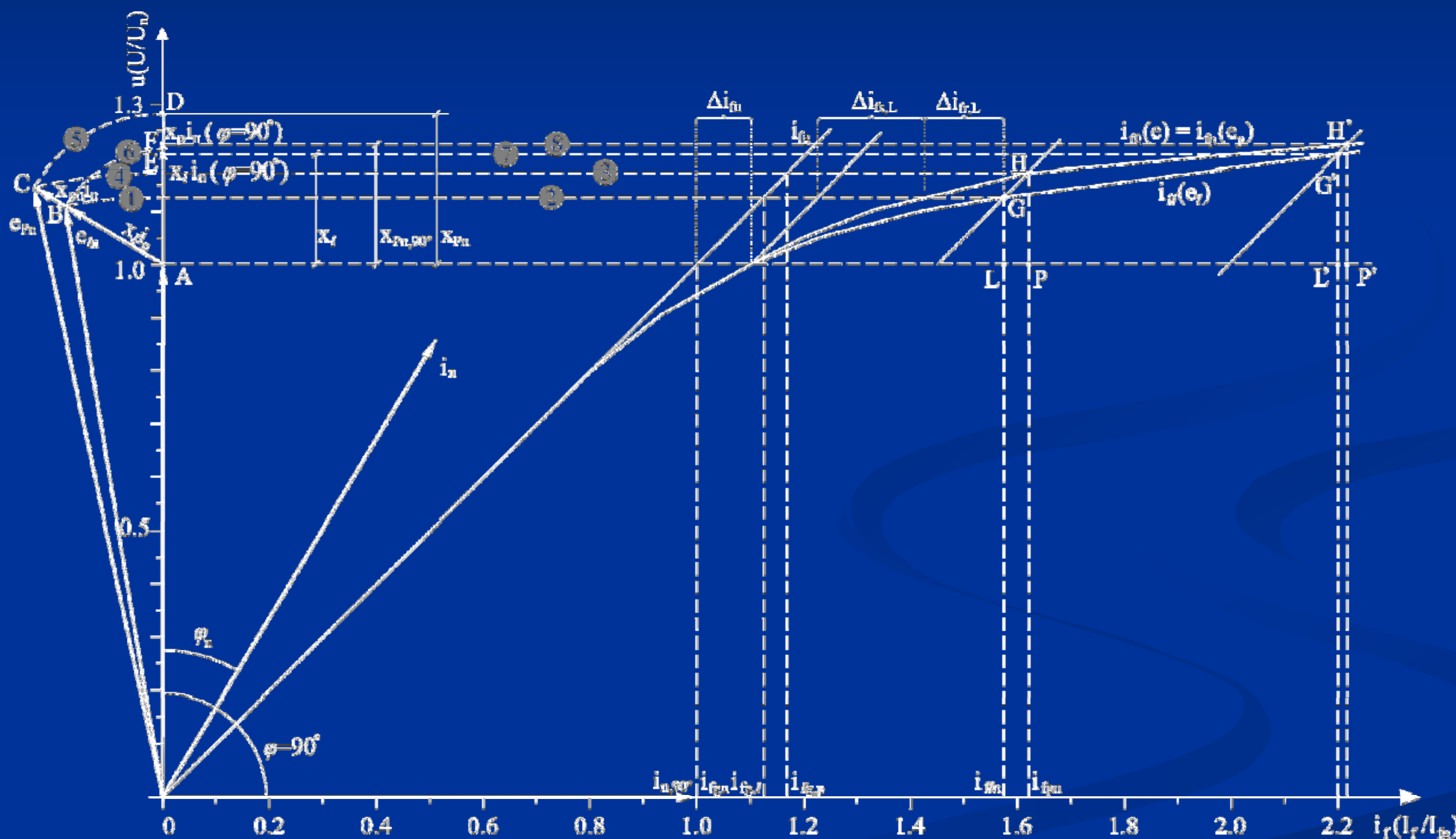


Fig. 3: Vector diagrams of electromotive forces (e_P) and (e_l), and procedure for determining the Potier reactance (x_P)

- x_{Pn} for the rated generator regime ($u = u_n$, $i = i_n$ and $\varphi = \varphi_n$), from 1-6;

- $x_{Pn,90}$ for the reactive load with rated current (u_n, i_n and $\varphi = 90^o$), from 7-8; $\mathbf{x_{Pn,90} < x_{Pn}}$

Potier reactance dependence on the load and the new method for its determination

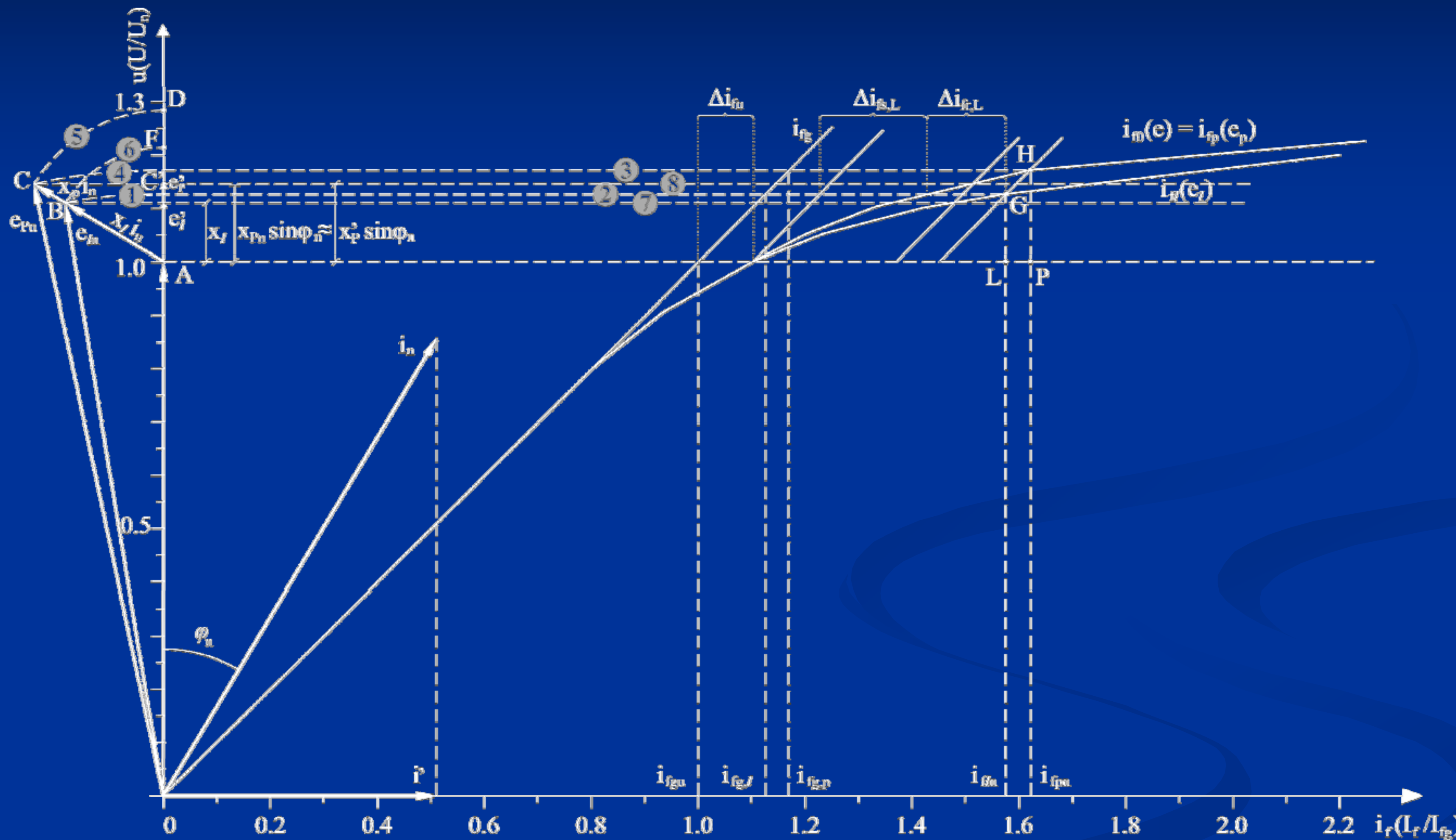


Fig. 4: Vector diagrams of electromotive forces (e_P) and (e_l), and procedure for determining the Potier reactance (x_P)

- x_{Pn} *for the rated generator regime* ($u = u_n$, $i = i_n$ *and* $\varphi = \varphi_n$)*, from 1-6;*
- $\boldsymbol{x_{P,90}(i_{an} \sin\varphi_n)}$ *for the reactive load with armature current* $\boldsymbol{i_{a,90} = i_{an} \sin\varphi_n}$ $u=u_n$*, and* $\varphi = 90^o$)*, from 7-8,*

$$\boldsymbol{x_{Pn} \approx x_{P,90}(i_{an} \sin\varphi_n)}$$

Potier reactance dependence on the load and the new method for its determination

- The Potier reactance value for the rated regime (x_{Pn}) is approximately equal to the value of the reactive load $i' = i_{an} \cdot sin\varphi_n$ ($u = u_n$, $i' = i_{an} \cdot sin\varphi_n$ i $\varphi = 90^o$), i.e. (Figure 4):

$$x_{P,n} = x'_{P,90}, \text{ for } i_{90}' = i_{an} \cdot sin\varphi_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

- This rule was verified on the example of generator GTHW 360 (360 MW) for regimes around the nominal ($P_G \approx P_{Gn}$ and $Q_G \approx Q_{Gn}$), i.e. by comparison of:
  - measured values ($I_{f,meas}$), and
  - calculated values ($I_{f,calc}$), on the basis of Potier reactances (x_P) for $Q_{G,cos\varphi=0} \approx Q_{Gn}$.

  And, it is obtained

$$I_{f,calc} = I_{f,meas} \pm 0.4\%$$

Potier reactance dependence on the load and the new method for its determination

- Based on the equivalence (1) and Figure 4, it is possible to write a general equivalence

$$x_{P,n} = x'_{P,90}, \text{ for } i_{90}' = i_a \cdot \sin\varphi_n \text{ ....} \quad (2)$$

- The explanation is based on following facts:
  - The electromotive force has approximately the same values ($e_P \approx e_\ell$), in
    - reactive load region $i' = i_{an} \cdot \sin\varphi_n$ and
    - nominal generator region, i.e. $e'_{\ell 90} \approx e_{\ell n}$=0B and $e'_{P90} \approx e_{Pn}$ =0C (Figure 4),
  - The corresponding components of the magnetic leakage of
    - the rotor excitation coil and
    - the armature winding (on the stator),

    depend mostly on the reactive load.

Conclusion

- Based on these results, it is concluded that the Potier reactance values mostly depend on the reactive load component ($i_{aQ} = i_a \cdot sin\varphi$). The above hypothesis was verified by
  - general qualitative analysis, and
  - experiment, for loads about rated active and reactive power, for generator GTHW 360 (360 MW)

- Author proposes that Potier reactance should be determined from reactive load test for three values of armature current.

Thank you for your attention