On the Influence of Synchronous Generator on Disconnection Processes in Electric Power Systems Comprising Generator Circuit Breakers

CORNELIA A. BULUCEA\(^1\), MARC A. ROSEN\(^2\), DORU A. NICOLA\(^1\), NIKOS E. MASTORAKIS\(^3\) and CARMEN A. BULUCEA\(^4\)

\(^1\)University of Craiova, Faculty of Electrical Engineering, Craiova 200440, Romania;
\(^2\)Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON, L1H 7K4, Canada;
\(^3\)Technical University of Sofia, Industrial Engineering Department, Sofia, Bulgaria & Military Institutions of University Education (ASEI), Hellenic Naval Academy, Piraeus 18539, Greece;
\(^4\)University of Medicine and Pharmacy of Craiova, Craiova 200349, Romania;

E-Mails: abulucea@gmail.com (C.A.B.); marc.rosen@uoit.ca (M.R.); dorunicola@gmail.com (D.N.); mastorakis4567@gmail.com (N.M.); carmen.bulucea@gmail.com (C.B.)

Abstract: This paper is a sequel study by the authors on the electric connection circuits comprising the generator circuit-breakers (GCBs) at generator terminals, which was undertaken since GCBs offer many advantages related to the sustainability of an electric power station. This paper extends other studies of the authors which have examined the exergetic transformation chain at the interruption current transient process in an electric power system that comprises the generator circuit-breaker, as well as the transient recovery voltage (TRV) which appears after the interruption of a short-circuit fed by the synchronous generator. For achieving the TRV equivalent configuration the authors applied the method of operational symmetrical components, and utilized the operational impedances of synchronous generator and/or of main transformer, depending on the fault location. Since the TRV which appears after the interruption of a short-circuit fed by the generator may be considered like an oscillation with the oscillation factor and the rising rate (RR) of the TRV established by the electrical machine parameters (resistance, inductance, and capacitance), in this paper we assess the operational impedances with concentrated parameters of the synchronous generator through an analysis of the generator behaviour over the interruption processes in an electric power system comprising generator circuit-breakers. Thus, adopting the pattern of an ideal synchronous machine and applying the overlapping principle and coordinates transformation, the operational equations are obtained of a synchronous generator at sudden load variation. Further the synchronous generator dynamic inductance during rapid processes is determined, as is the simplified operational circuit of the synchronous generator at the first phase current interruption.

Key-Words: electric arc; generator circuit-breaker; sustainability, synchronous generator; transient recovery voltage

1 Introduction

A generator circuit-breaker is located between the generator and the main step-up transformer, and this location influences the operating conditions [1-8].

In previous studies [9-14] the authors examined the usefulness of sustainability concepts for analyzing systems which transform energy, including the generator circuit-breaker (GCB) disconnection process. A sustainability assessment of the current interruption requirements of a GCB addresses the main stresses on the generator circuit breaker, revealing that the GCB current interruption requirements are significantly higher than for the distribution network circuit breakers.

The configuration of the key fault current encountered by the generator breaker (GB) is represented in Figure 1, and details are as follows:
- Faults at location \(K_1\) are called Generator (G)-source faults or Generator-fed faults (which can be insulated or grounded three-phase and two-phases short-circuits);
- Faults at location \(K_2\) are called System-source faults or Transformer (MT)-fed faults (which can be insulated or grounded three-phase and two-phases short-circuits);
Faults at location K₁ are called Generator-fed faults, on the high voltage side of the main step-up transformer (which can be insulated or grounded three-phase and two-phases short-circuits, as well as single-phase short-circuits).

To interrupt these kinds of faults, generator circuit-breakers are submitted to specific stresses:

(a) The GCBs must be capable of interrupting not only the highly symmetrical fault current, but also the higher asymmetrical fault currents resulting from high d.c. components of the fault current. Here arises a sustainability requirement for generator circuit-breakers which are subjected to a unique demanding condition, called delayed current zeros [12,14].

(b) Since circuit breakers interrupt on the current zero crossing, generator circuit-breakers must be able to withstand longer arcing times and greater electrical, thermal and mechanical stresses when interrupting such faults [3,14].

(c) Just after the short-circuit current interruption by the generator circuit-breaker (when the GCB has been subjected to a very high temperature plasma arc), between its opened contacts arises the transient recovery voltage (TRV) which constitutes the most important dielectric stress after the electric arc extinction [2,8,14].

The authors previously utilized the framework of sustainability to address the GCB specific stresses [12–14]. Since the magnitude and shape of the TRV occurring across the generator circuit-breaker are critical parameters in the recovering gap after the current zero, for the case of the generator-fed faults (location K1) we have modeled [14] the equivalent configuration with operational impedances for the TRV calculation, taking into account generator parameters, on the basis of the operational symmetrical components (o.s.c.) method. The operational symmetrical components of the phase voltages and currents - on the synchronous generator side - are related by operational equations, of the form:

\[ U_{g^+}(p) = Z_{g^+}(p) \cdot I_{g^+}(p) \]
\[ U_{g^{-}}(p) = Z_{g^{-}}(p) \cdot I_{g^{-}}(p) \]
\[ U_{g^0}(p) = Z_{g^0}(p) \cdot I_{g^0}(p) \]

where \( Z_{g^+}(p) \), \( Z_{g^{-}}(p) \) and \( Z_{g^0}(p) \) denote the phase operational impedances of the synchronous generator in the symmetrical regimes by positive, negative and zero sequences.

Applying the o.s.c. method, the operational image of the TRV occurring across the GB poles after the current interruption have been determined. If the phase current interruption is modelled by the current injection \( i_k \) - equal but opposite to the eliminated one - the operational image of the TRV occurring across the generator breaker can be expressed in mathematical form:

\[ U_o(p) = -I_s(p) \cdot Z_o(p) \]

where \( I_s(p) \) represents the operational image of the switched current and \( Z_o(p) \) the operational equivalent impedance across the generator circuit breaker.

The currents of short-circuits in \( K_1 \) (and interrupted by GB) are fed by the synchronous generator (G).

Applying the o.s.c. method, the TRV operational equation take on the form:

\[ U_o(p) = I_s(p) \cdot \frac{3 Z_{g^+}(p) \cdot 3 Z_{g^{-}}(p)}{3 Z_{g^+}(p) + 3 Z_{g^{-}}(p)} \]

Equation (3) allows the operational representation in Figure 2a. When \( Z_{g^+}(p) = Z_{g^{-}}(p) = Z_g(p) \), Equation (3) becomes:

\[ U_o(p) = 1.5 \cdot I_s(p) \cdot Z_g(p) \]

with the operational circuit corresponding to Fig. 2b.

![Operational equivalent circuit](image)

**Fig. 2 Operational equivalent circuit:** (a) TRV at insulated three-phase short-circuit disconnection, with \( Z_{g^+}(p) \neq Z_{g^{-}}(p) \); (b) TRV at insulated three-phase short-circuit disconnection, with \( Z_{g^+}(p) = Z_{g^{-}}(p) = Z_g(p) \)

Applying the method of operational symmetrical components to determine the TRV which appears after the interruption of a short-circuit fed by the generator or the main transformer represents an original contribution of the authors of that study. The method is suitable for application at the poles of any circuit breaker, for any eliminated fault type.
(fed by the main transformer or by the synchronous generator), if the elements and configuration of the power network are known.

The TRV which appears after the interruption of a short-circuit fed by the generator may be considered like an oscillation with the oscillation factor and the rising rate (RR) of TRV established by the electrical machine parameters: resistance, inductance, and capacitance. Note that, in analytical studies, the calculation of the transient recovery voltage at the circuit breakers situated in the proximity of the generators is made on basis of the equivalent configurations with concentrated parameters. Consequently, addressing the assessment the operational impedances with concentrated parameters of the synchronous generator through an analysis of the generator behavior over the interruption processes in an electric power system comprising generator circuit-breakers follows in this study.

2 Equations of Synchronous Generator at Electric Perturbation

In this study we have been adopted the usual hypotheses to define the ideal synchronous machine [15-18], neglecting the iron saturation and hysteresis phenomena and ferromagnetic core losses. The ideal synchronous machine will have the same self and mutual leakage reactances of the stator as the substituted real machine. In terms of the effects that depend on the rotor position, the idealization goes far to considering each stator winding as having a sinusoidal distribution. The positive directions (of voltage and current) are taken into account according to the generator convention.

In Figure 3 there are specified the axes of the phases A, B and C of the ideal synchronous machine, as well as the phase axes (α, β) and (d, q), respectively, of the equivalent synchronous machines; the rotor rotating sense being also specified in Figure 1. The magnetization directions of currents i_A, i_B, i_C, and i_α, i_β, respectively, are fixed in the reference frame related to stator, whereas the magnetization directions i_d, i_q are fixed in the reference frame related to rotor.

Since through a synchronous generator perturbation a sudden transformation of the operation conditions is understood [15,16,19], we can assume that the first phase current interruption by the generator circuit-breaker constitutes a synchronous generator perturbation. Because of the extremely small perturbation duration, the voltage regulator action is imperceptible. For the same reason it can as well be considered that the rotor position (specified by the angle γ₀, measured between the axis of phase A and the longitudinal axis d) remains unchanged over the whole perturbation duration.

The sudden variation of the current on one phase (for instance, on phase A) will determine the sudden variations ∆i_d and ∆i_q of the equivalent machine currents in the frame coordinates (d, q), as follows:

\[
\Delta i_d = (2 \Delta i_d \cdot \cos \gamma_0) / 3 ; \quad \Delta i_q = -(2 \Delta i_d \cdot \sin \gamma_0) / 3 \quad (5)
\]

This means the synchronous generator will be submitted to a transient regime. Consequently, at the first moment, assuming the superconducting rotor circuits, the variations of the fluxes linked to the equivalent machine windings in coordinates d, q (caused by the sudden variations of the currents) will be:

\[
\Delta \Psi_d = L_d'' \cdot \Delta i_d ; \quad \Delta \Psi_q = L_q'' \cdot \Delta i_q
\]

Considering the recurrence relations between the coordinates (d, q) and (α, β) [3-5):

\[
\Delta i_d = \Delta i_\alpha \cdot \cos \gamma_0 + \Delta i_\beta \cdot \sin \gamma_0
\]

\[
\Delta i_q = -\Delta i_\alpha \cdot \sin \gamma_0 + \Delta i_\beta \cdot \cos \gamma_0
\]

it can be hypothesized that these sudden variations ∆i_d and ∆i_q would be determined by some correspondent variations ∆i_α and ∆i_β (unknown, for the time being) of the currents flowing through the stator windings (α, β) of the equivalent machine.

Similarly, the fluxes’ variations ∆Ψ_α and ∆Ψ_β are determined:

\[
\Delta \Psi_\alpha = \Delta \psi_\alpha \cdot \cos \gamma_0 - \Delta \psi_\beta \cdot \sin \gamma_0
\]

\[
\Delta \Psi_\beta = \Delta \psi_\alpha \cdot \sin \gamma_0 + \Delta \psi_\beta \cdot \cos \gamma_0
\]

If relations (7) are substituted in (6), with the further results in (8), we obtain the dependencies among the fluxes’ variations ∆Ψ_α, ∆Ψ_β and the corresponding currents’ variations ∆i_α, ∆i_β:
\[
\Delta \psi_a = (L_d'' \cos^2 \gamma_0 + L_q'' \sin^2 \gamma_0) \Delta i_a + \\
+ (L_d'' - L_q'') \sin \gamma_0 \cos \gamma_0 \Delta i_\beta \\
\Delta \psi_\beta = (L_d'' - L_q'') \sin \gamma_0 \cos \gamma_0 \Delta i_a + \\
+ (L_d'' \sin \gamma_0 + L_q'' \cos \gamma_0) \Delta i_\beta \\
\] (9)

With the supplementary notations:

\[
L_s = (L_d'' + L_q'')/2 \\
L_q = (L_d'' - L_q'')/2 \\
\] (10)
equation (9) takes the form:

\[
\Delta \psi_a = (L_s + L_r \cos 2 \gamma_0) \Delta i_a + L_r \sin 2 \gamma_0 \Delta i_\beta \\
\Delta \psi_\beta = L_r \sin 2 \gamma_0 \Delta i_a + (L_s - L_r \cos 2 \gamma_0) \Delta i_\beta \\
\] (11)

The fluxes' variations \(\Delta \psi_a\) and \(\Delta \psi_\beta\) implicitly determine further voltage variations. These will result from the synchronous generator voltage equations in coordinates \(\alpha, \beta\):

\[
\Delta u_a = -R \cdot \Delta i_a - \frac{d}{dt} \Delta \psi_a \\
\Delta u_\beta = -R \cdot \Delta i_\beta - \frac{d}{dt} \Delta \psi_\beta \\
\] (12)
or after substituting the expressions of \(\Delta \psi_a\) and \(\Delta \psi_\beta\):

\[
\Delta u_a = -R \Delta i_a - (L_s + L_r \cos 2 \gamma_0) \frac{d}{dt} \Delta i_a + L_r \sin 2 \gamma_0 \frac{d}{dt} \Delta \psi_\beta \\
\Delta u_\beta = -R \Delta i_\beta - (L_s - L_r \cos 2 \gamma_0) \frac{d}{dt} \Delta i_\beta \\
\] (13)

Writing with capitals the operational Laplace images of voltages and currents, the system of equations (13) becomes:

\[
\Delta U_a = -[R + (L_s + L_r \cos 2 \gamma_0) p] \Delta I_a + L_r \sin 2 \gamma_0 \frac{d}{dt} \Delta I_\beta \\
\Delta U_\beta = -L_r \sin 2 \gamma_0 \frac{d}{dt} \Delta I_a + [R + (L_s - L_r \cos 2 \gamma_0) p] \Delta I_\beta \\
\] (14)

Equations (14) ascertain, in a general case, the link between the current variations and voltage variations at the terminals of the windings \(\alpha, \beta\) of the synchronous generator. In the context of some local restrictions, these equations can be simplified, both for short-circuit and load disconnection.

3 Dynamic Inductance

In the study of the transient processes, which appear at the interruption of short-circuits fed by the generator or at load disconnection, is rooted the idea that the equivalent phase inductance should be equal or proportional to the subtransient inductance \(L_d''\) [15,16,17]. Sometimes this is corrected with factors below par, which differ from an author to another. There have been other proposals as well. According to some study findings [20-21] this parameter is connected to \(L_d''\) and \((L_d'' + L_q'')/2\), whereas other studies [22-23] consider it equal to \((L_d'' L_q'')/2\). Still, considering the equivalent phase inductance of synchronous generator equal to \(L_d''\) or \(L_q''\), phenomenologically this idea implies to admit unconditionally that at the disconnection moment the rotor would be aligned (or in quadrature) with the axis of the phase in which the current is first interrupted, and the machine magnetic field would have an identical spectrum with that of the considered subtransient regime. Furthermore, in such processes the synchronous generators have been modelled through a succession of RLC parallel cells which are connected in series. Besides, the technical literature does not entail physical or mathematical justification of such considerations.

In the current interruption processes of a phase stator winding it should be considered the dynamic inductance of synchronous generator [16], defined as:

\[
L_{d.g.}^\alpha = \frac{\Delta \psi_a}{\Delta i_a} \\
\] (15)

Since in such processes [19] \(u_0 = 0\) or \(u_0 = \text{const.}\), we obtain \(\Delta u_0 = 0\). If at the first moment the windings are considered as superconducting (\(R = 0\)), the restriction \(\Delta u_0 = 0\) substituted in equation (12.b) will lead to:

\[
- \frac{d}{dt} \Delta \psi_\beta = 0 \Rightarrow \Delta \psi_\beta = \text{const.} = 0 \\
\] (16)

From equation (11.b) it is obtained the recurrence relation:

\[
\Delta i_\beta = -\frac{L_r \cdot \sin 2 \gamma_0}{L_s - L_r \cos 2 \gamma_0} \cdot \Delta i_a \\
\] (17)

which is used to determine the flux variation \(\Delta \psi_a\):

\[
\Delta \psi_a = \frac{L_d'' + L_q''}{L_s - L_r \cos 2 \gamma_0} \cdot \Delta i_a \\
\] (18)

Further it is directly emphasized the equivalent phase dynamic inductance of the synchronous generator:

\[
L_{d.g.} = \frac{L_d'' - L_q''}{L_s - L_r \cos 2 \gamma_0} \\
\] (19)

With the notations (10) the dynamic inductance (19) can be written as the form:

\[
L_{d.g.} = \frac{L_d'' \cdot L_q''}{L_d'' \sin^2 \gamma_0 + L_q'' \cos^2 \gamma_0} = \frac{L_q''}{\sin^2 \gamma_0} + \frac{L_d''}{\cos^2 \gamma_0} \\
\] (20)

The equivalent circuit corresponding to relation (20) is represented in Figure 4.

As a result, over the transient interruption processes the synchronous generator dynamic inductance depends both on the subtransient inductances \((L_d''\) and \(L_q''\)), and on the instantaneous rotor position \(\gamma_0\) at the perturbation moment. Referring to \(\gamma_0\), the dynamic inductance takes distinct values for
if \( 0 \leq \gamma_0 \leq \pi \), after which they are recurring. Among the characteristic values of the dynamic inductance there are encountered both \( L_d'' \) and \( L_q'' \), as well as their harmonic average.

The dynamic inductance average value in the interval \([0,\pi]\), determined with the relation:

\[
L_{d,g,med} = \frac{1}{\pi} \int_0^\pi \frac{L_d'' \cdot L_q''}{\sin^2 \gamma_0 + L_q'' \cdot \cos^2 \gamma_0} \, d\gamma_0
\]  

is obtained (after an intermediate calculation) in the form:

\[
L_{d,g,med} = \sqrt{L_d'' \cdot L_q''} \tag{22}
\]

Solely adopting this point of view the assumption emphasized in [22] takes a physical justification.

The dynamic inductance r.m.s. on the interval \([0,\pi]\) is ascertained with the relation:

\[
L_{d,g,ef} = \sqrt{\frac{1}{\pi} \int_0^\pi \left( \frac{L_d'' \cdot L_q''}{\sin^2 \gamma_0 + L_q'' \cdot \cos^2 \gamma_0} \right)^2 \, d\gamma_0} \tag{23}
\]

leading finally, after the integral assessment, to the form below:

\[
L_{d,g,ef} = \sqrt{\frac{1}{2} \left( L_d'' + L_q'' \right)^2} \tag{24}
\]

which is exactly the geometric average of the arithmetic and geometric averages, respectively, of the subtransient inductances \( L_d'' \) and \( L_q'' \).

Moreover, among the possible values of the dynamic inductance there are ascertainment the relations: \( L_d'' < L_{d,g,ef} < L_{d,g,med} < \left( L_d'' + L_q'' \right)/2 < L_q'' \).

One could highlight that the selection hitherto of the subtransient inductance \( L_d'' \) as the equivalent phase inductance of the synchronous generator in the study of the transient interruption processes takes a physical sense solely in approximate calculation.

Besides, the existence over the disconnection process duration of high frequency leakage flux creates all premises to accept that the phase equivalent inductance would be smaller than that corresponding to the industrial frequency reactance \( X_q'' \). Solely in this context the recommendations of other studies could be plausible, and we are directed towards the idea that in such processes the phase inductance of the synchronous generator would be:

\[
L_g = \lambda_g \cdot L_d'' \tag{25}
\]

where \( \lambda_g \) is a sub-unit numerical factor.

Usually \( \lambda_g = 0.6-0.85 \) and it could vary from one generator to another.

### 4 First Phase Current Interruption

The initial conditions corresponding to the three-phase short-circuit are specified by \( u_{a0}(t) = u_{a0}(t) = u_{c0}(t) \). After the current interruption in phase \( A \), the synchronous generator is passing for a short time in a two-phases short-circuit, with \( u_{a0}(t) = u_{c0}(t) \). Calculation of voltage at the terminals of winding \( \beta \):

\[
u_{\beta} = \left\{ u_{a} - u_{c} \right\} / \sqrt{3} \tag{26}
\]

emphasizes that on whole perturbation duration \( u_{\beta} = 0 \), and consequently \( \Delta U_{\beta} = 0 \) as well.

Therefore, the current variations \( \Delta I_a \) and \( \Delta I_\beta \) are linked by the relation:

\[
\Delta I_\beta = -\frac{L_g \cdot \sin 2 \gamma_0 \cdot p}{R + (L_s \cdot L_y \cdot \cos 2 \gamma_0) \cdot p} \Delta I_a \tag{27}
\]

By substituting further the relation above in expression (14.a) we obtain:

\[
\Delta U_a = -\frac{R + 2 \cdot R \cdot L_a \cdot p + (L_s \cdot L_y) \cdot p^2}{R + (L_s \cdot L_y \cdot \cos 2 \gamma_0) \cdot p} \Delta I_a \tag{28}
\]

Equation (28) constitutes precisely the operational equation of the synchronous generator in the coordinates \( a,\beta \) at the current interruption in phase \( A \).

In the case of the load disconnections, after the first phase current interruption, the synchronous generator moves to operate in an unsymmetrical regime.

Noting that the line voltage \( u_{ac} = u_{a0} - u_{c0} \) remains actually unchanged, and also that \( u_{\beta} = u_{ac} / \sqrt{3} \), we determine that in this case as well \( \Delta U_{\beta} = 0 \) over the whole perturbation duration. Consequently, in the framework of load disconnection, the synchronous generator behavior at the first phase current interruption will be depicted as well by equation (28).

Based on the notations (10) the equation (28) we obtain the form:

\[
\Delta U_a = -\frac{(R + pl_{a''}) \cdot (R + pl_{d''})}{(R + p l_{d''} \cdot \sin^2 \gamma_0 + (R + p l_{q''}) \cdot \cos^2 \gamma_0)} \Delta I_a \tag{29}
\]

or

\[
\Delta U_a = - \Delta I_a \left\{ \frac{1}{\frac{R}{\sin^2 \gamma_0} + \frac{l}{\sin^2 \gamma_0}} + \frac{1}{\frac{R}{\cos^2 \gamma_0} + \frac{l}{\cos^2 \gamma_0}} \right\} \tag{30}
\]
Since the coordinates $\alpha$ of voltages and currents are determined with the following relations:

$$
\begin{align*}
    u_a &= \frac{2}{3}(u_A - \frac{u_B + u_C}{2}) \ ; \ i_a &= \frac{2}{3}(i_A - \frac{i_B + i_C}{2}) \\
    2u + i - i(3) &= i(2) = i(C) \\
    2u + i - i(3) &= u(C) = u(B) \\
    u &= i(\alpha) \\
    \end{align*}
$$

and the considered perturbation solely affects the quantities of phase A, we directly find in operation that:

$$
\Delta U_A = 2/3 \Delta U_A : \Delta I_A = 2/3 \Delta I_A \tag{32}
$$

Further equation (30) takes the form:

$$
\Delta U_A = -\Delta I_A \left( \frac{R}{\sin^2 \gamma_0} + \frac{pL_q}{\sin \gamma_0} \right) = \frac{1}{\cos \gamma_0} + \frac{pL_q}{\cos \gamma_0} \tag{33}
$$

Equation (33) allows settling the simplified operational circuit, without considering the capacitance of the synchronous generator at the first phase interruption, as depicted in Figure 5. This is used to assess the equivalent phase circuit structure of the synchronous generator during the current interruption process, with the aim to determine the transient recovery voltage across the generator circuit breaker.

![Figure 5. Simplified operational circuit of synchronous generator at first phase current interruption](image)

**5 Synchronous Generator Operational Circuit at First Phase Current Interruption**

Studies on synchronous generator windings over the interruption processes [19,22] have emphasized the finding that the windings could be seen as long straight conductors. In such situation the capacitance is mainly distributed between each winding and the ferromagnetic stator core, because both the capacitive coupling among the phase windings and the longitudinal capacitance (among winding turns) are very small and can be neglected.

Analyzing the first phase current interruption process when it is considered the equivalent concentrated capacitances $C_{eg}$ (see Figure 6), it is ascertained that through the stator winding A:

$$
\Delta I_A(p) = I_{cap}(p) - I_A(p) \tag{34}
$$

Still, one could note that the capacitance presence will determine further the formation of an oscillatory circuit in which, because of the perturbation, high frequency currents ($10$-$30$ kHz) will appear. The magnetic field created in the synchronous generator by these high frequency currents has a spectrum completely different from the useful magnetic fields, rather it having been approached to the leakage field spectrum. Consequently, this field does not depend on the rotor position or on iron saturation or excitation degree, being influenced mainly by the constructive machine elements. In this field, each phase winding will have the same inductance $L_g$ (see Equation (25)) which is completely different from $L_d$" or $L_q"$, and the same resistance $R_g > R$ (because of the specific phenomena at the oscillation frequency).

If in equation (33) the inductances $L_d"$ and $L_q"$ are replaced by $L_{eg}$, the resistance $R$ is replaced by $R_p$, and we take into consideration relation (34), in which:

$$
I_{cap} = p \cdot C_{eg} \cdot \Delta U_A \tag{35}
$$

the following results:

$$
\Delta U_A = \left( p \cdot C_{eg} + \frac{1}{R_g + p \cdot L_{eg}} \right) \cdot I_A \tag{36}
$$

Since the equivalent phase resistance $R_g$ is relatively small (namely, maximum $(8$-$10)R$), one could assume that the strong damping of the oscillations of the transient recovery voltage can be justified solely on basis of a conductance of losses of the winding insulation at high frequency. This means we admit a parallel circuit for the capacitor [16,18], as depicted in Figure 7, where:
\[ G_g = G_0 + \omega \cdot C_{\text{max}} \cdot \sin \delta_h \]
\[ C_g = C_{\text{max}} \cdot \cos \delta_h \]

where \( G_0 \) denotes the d.c. conductance; \( C_{\text{max}} \) the apparent capacitance over the loading cycle (equal to \( Q_{\text{max}}/U_{\text{max}} \)); and \( \delta_h \) the hysteresis losses’ angle (from the cycle area).

The split of the total losses into conduction losses and hysteresis losses has no relevance in applications. Therefore the equivalent circuits are utilized with elements determined directly through the measurement of losses.

Thus, if \( \delta = \pi/2 - |\varphi_e| \) is the total losses’ angle and \( tg \delta = G_g / \omega \cdot C_g \) 2 is the losses’ factor, the following result:

\[ G_g = \omega \cdot C_g \cdot tg \delta \]
\[ G_g = I_{cap} \cdot \sin \delta/\Delta U_A \]
\[ C_g = I_{cap} \cdot \cos \delta/\Delta U_A \]

Without a large error, in applications it may be determined that:

\[ C_g = C_{eg} ; G_g = \omega \cdot C_{eg} \cdot tg \delta \] (38)

Consequently, the operational circuit (36) becomes:

\[ \Delta U_A = \{ G_g + p \cdot C_g + \frac{1}{R_g + p \cdot L_g} \} \cdot I_s(p) \] (39)

With the notation \( \Delta I_{Ab} = 0 - I_A \) for the current variation in the busbar corresponding to phase A over the current interruption, equation (39) can be rewritten in the form:

\[ \Delta U_A = \{ G_g + p \cdot C_g + \frac{1}{R_g + p \cdot L_g} \} \cdot (-\Delta I_{Ab}) \] (40)

In Figure 8 we depict the operational circuit corresponding to the equation above. This circuit is actually the phase operational representation of the synchronous generator at the disconnection processes’ frequency.

### 6 Conclusion

Modelling of the transient recovery voltage of circuits highlights aspects that have direct implications on commutation equipment. The method of operational symmetrical components can be applied to assess the operational equations and configurations of the transient recovery voltage which appears at the generator circuit-breaker terminals after the interruption of a three-phase short-circuit fed by a synchronous generator.

Further, these findings have to be followed by the assessment of the structure of the operational impedances of the generator \( Z_g^- (p) \) and \( Z_g^+ (p) \) taking into consideration the concentrated electric parameters of the synchronous generator. During the interruption current transient processes, the electromagnetic phenomena in the synchronous generator are complex, and interactions of the generator with the electric network occur. Modeling of concentrated equivalent parameters of the synchronous generator at perturbations caused by current interruption transient processes is achieved in this study through an approach based on sustainability concepts. Adopting the pattern of ideal synchronous machine and applying the overlapping principle and the coordinates transformation, we obtain the operational equations of synchronous generator at sudden load variation. Further the synchronous generator dynamic inductance during rapid processes is emphasized and the simplified operational circuit of the synchronous generator at the first phase current interruption is ascertained.

As a final conclusion the importance is highlighted of the components \( (\alpha, \beta) \). They provide a useful physical point of view concerning the phase current interruption, even though the analysis of transient recovery voltage is based on symmetrical components’ method.
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