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Synoptic Approach of Synchronous Generator on Disconnection Processes in Electric Power Systems Comprising Generator Circuit Breakers

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Abstract: This paper is a sequel to a study by the authors of electric power systems comprising the generator circuit-breakers (GCBs) at power plant generator terminals. A sustainable 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. Hence, generator circuit-breakers are subject to unique demanding conditions caused by specific stresses, namely: high asymmetrical fault currents resulting from high d.c. components of the fault current; greater electrical, thermal and mechanical stresses when interrupting longer arcing time faults; and important dielectric stress after the electric arc extinction caused by the transient recovery voltage (TRV). This paper extends other studies of the authors on the energetic and 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 which appears after the interruption of a short-circuit fed by the synchronous generator or by the main step-up transformer. For achieving the TRV equivalent configuration the authors applied the method of operational symmetrical components (o.s.c.), and utilized the operational impedances of the synchronous generator and of the main transformer, depending on the fault location. Modeling the transient recovery voltage of circuits emphasizes aspects with direct implications on commutation equipment. Thus, the o.s.c. method can be applied at the poles of any breaker, for any eliminated fault type, if the network configuration and elements are known. The TRV, which appears after the interruption of a short-circuit fed by the generator, may be considered like an oscillation, where the oscillation factor and the rising rate (RR) of the TRV are established by the electrical machine parameters: resistance, inductance and capacitance. Consequently, 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. These findings allow for simulations of the transient recovery voltage and comparisons with experimental results.

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

1 Introduction

Following the notion that life on Earth demonstrates sustainable energy conversion [1-4], we aim to highlight that an approach to an electrical power system according to the patterns defined within the sustainability framework could provide a synoptic view of electromagnetic interaction phenomena within an electric power network entailing a generator circuit-breaker (GCB) at the terminals of the synchronous generator of an electric power station [5-7].

The electric connection circuits of power stations encompass GCBs at the generator terminals, since the presence of that electric equipment is related to the sustainability of a power plant [4-15]. The location of a GCB, between the generator and the

main step-up transformer, influences the operating conditions, and a sustainable assessment of the GCB requirements addresses the main stresses on generator circuit breakers, revealing that the GCBs are significantly more difficult to apply to some operating regimes than classical network circuit-breakers [5-20].

In previous studies [16-20] 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.

In our previous studies [16-20] we have shown the configuration of the key fault current encountered by the generator circuit breaker see Fig.1), namely: generator-fed faults (at location K_1) which can be insulated or grounded three-phase and two-phases short-circuits; transformer-fed faults (at location K_2) which can be insulated or grounded three-phase and two-phases short-circuits; and generator-fed faults, on the high voltage side of the main step-up transformer (at location K_3)which can be insulated or grounded three-phase and two-phases short-circuits, as well as single-phase short-circuits.
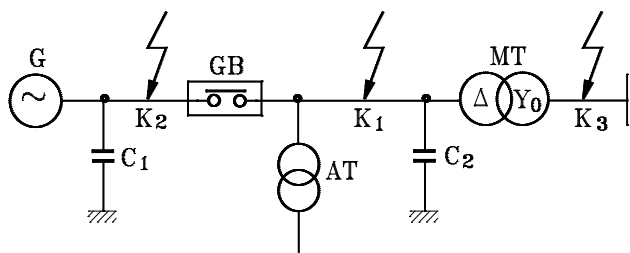

Fig. 1 Possible faults interrupted
by a generator breaker (GB)

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 [5-10]. Here arises a sustainability requirement for generator circuit-breakers which are subjected to a unique demanding condition, called delayed current zeros [5,12,16].

(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 [5-17].

(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 [12-14, 16-20].

The authors utilized the framework of sustainability and addressed the GCB specific stresses through an exergy analysis of the transformation chain for the interruption current transient process in an electric power system that comprises the generator circuit-breaker [16-17]. The exergy balance of the interrupted circuit during the arc burning $X_{in} = X_{out} + X_{stored}$ emphasizes that the stored exergy X_{stored} is represented by the energy embedded in the magnetic field of the generator windings, corresponding to different states (sub-transient, transient and steady-state short-circuit), and embodied in the arc circuit [16-17].

After the electric arc extinction in the GCB, the magnitude and shape of the TRV occurring across the generator circuit-breaker are critical parameters in the recovering gap after the current zero and they are related to further transformation of the exergy stored in the interrupted alternating-current circuit that comprises the synchronous generator and the GCB.

In this article, for the case of the faults fed by the synchronous generator, we determine the TRV equivalent configuration with operational impedances, taking into account the generator parameters, and applying the operational symmetrical components method.

2 Modelling of Transient Recovery Voltage (TRV) during Interruption of Short-circuits Fed by the Synchronous Generator

The dielectric strength within the extinction chamber of the circuit-breaker should increase to a higher value than the TRV; otherwise the electric arc may rekindle [14]. The circuit-breaker capability in interrupting the new arc is strongly affected since the gas-filled space between the two electrodes has an important conductivity and this time the electric arc exergy would be entirely used in a destructive process.

Although the mechanical disconnection of the three phases is performed simultaneously, because

of the currents angle phase, the arcs extinction on the phases cannot be simultaneous. It first switches the arc on the phase so its current is passing first through zero. Therefore, the TRV on the three phases are different, even in the same three-phase fault interruption. Moreover, the TRV occurring across the generator circuit breaker depends both on the fault location and on the fault nature [14-23].

In the sustainability framework of this paper, we determine the TRV when the three-phase short-circuit fed by the synchronous generator is interrupted, using the *operational symmetrical components method* [16-20].

Basically, any non-symmetrical three-phase system of currents or voltages can be decomposed into two symmetrical three-phase systems (of different sequences) and a system of single-phase quantities [21,24-27]. The method application presumes linearity, having been used together with the symbolic representation, in a simplified complex, of the sinusoidal quantities. On basis of this transformation, applied to the phase instantaneous quantities of a three-phase system, we obtain complex quantities (which lose their physical significance), named +,-,0 *coordinates* or *instantaneous symmetrical components*. In the paper we follow the same idea of transformation of phase instantaneous quantities at the generator circuit-breaker terminals, in the moments subsequent to its disconnection.

The TRV occurring across the generator circuit breaker is considered only at $t > 0$, like a damped oscillation by high frequency (f>>50 Hz), starting from zero. Consequently, it is noted that both the TRV and the high frequency currents and voltages achieve the original function conditions.

Applying the operational calculus to the relations determined by the instantaneous symmetrical components method, we obtain the *operational symmetrical components* (o.s.c.) of the phase voltages and currents [16-20]. Moreover, the o.s.c. of the phase voltages and currents - on the synchronous generator side - are related by operational equations, of the form:

$$U_{g+}(p) = Z_{g+}(p) \cdot I_{+}(p)$$
$$U_{g-}(p) = Z_{g-}(p) \cdot I_{-}(p) \qquad (1)$$
$$U_{g0}(p) = Z_{g0}(p) \cdot I_{0}(p)$$

where $Z_{g+}(p)$, $Z_{g-}(p)$ and $Z_{g0}(p)$ 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:

$$U_{tr}(p) = - I_{k}(p) \cdot Z_{e}(p) \qquad (2)$$

where $I_k(p)$ represents the operational image of the switched current and $Z_e(p)$ the operational equivalent impedance across the generator circuit breaker.

We take into consideration the fault location in which the short-circuit currents that must be interrupted by GCB are fed by the synchronous generator. The considered generator has the stator three-phase windings connected by configuration *Y*. Consequently, the GB can be submitted to the *insulated or grounded three-phase and two-phases short-circuits*. In the paper, for illustration, we analyze the insulated three-phase short-circuit.

The TRV calculation configuration for the moment of the GB first phase opening is represented in Figure 2.
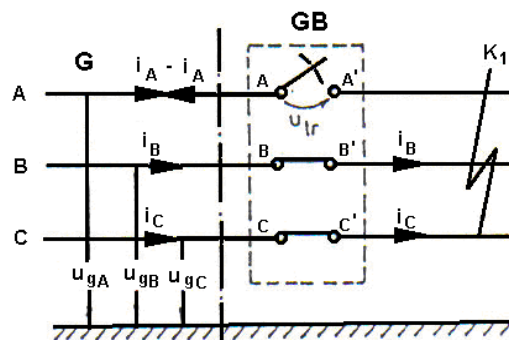
Fig. 2 First phase opening at insulated three-phase short-circuit

The current interruption has been considered as result of injection on phase *A* of the current $i_k = - i_A$, under the restriction

$$u_{gB} = u_{gC} \qquad (3)$$

and the TRV occurring at the pole *A-A'* is:

$$u_{tr} = u_{gA} - u_{gB} \qquad (4)$$

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

$$U_{tr}(p) = I_A(p) \cdot \frac{3 Z_{g+}(p) \cdot 3 Z_{g-}(p)}{3 Z_{g+}(p) + 3 Z_{g-}(p)} \qquad (5)$$

Equation (5) allows the operational representation in Figure 3a. When $Z_{g+}(p) = Z_{g-}(p) = Z_{g}(p)$, Equation (5) becomes:

$$U_{tr}(p) = 1,5 \cdot I_A(p) \cdot Z_{g}(p) \qquad (6)$$

with the operational circuit corresponding to Fig. 3b.
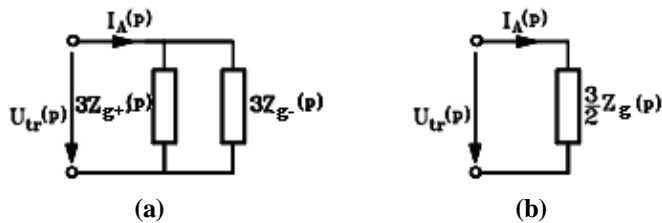
(a)   **(b)**

Fig. 3 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 this 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. 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. 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. Consequently, addressing the analysis of synchronous generator behaviour during an electromagnetic perturbation (caused by the current interruption) in an electric power system comprising generator circuit-breakers, and the assessment of the values of the concentrated equivalent parameters of the synchronous generators windings follow in this study.

3 Synchronous Generator Behaviour over the Interruption Processes in an Electric Power System Comprising a Generator Circuit Breaker

3.1 Equations of Synchronous Generator at Electric Perturbation

In this study we have been adopted the usual hypotheses to define the ideal synchronous machine [21, 24-27], 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 4 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 4. 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 [24, 27-29], 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 γ_0, measured between the axis of phase A and the longitudinal axis d) remains unchanged over the whole perturbation duration.
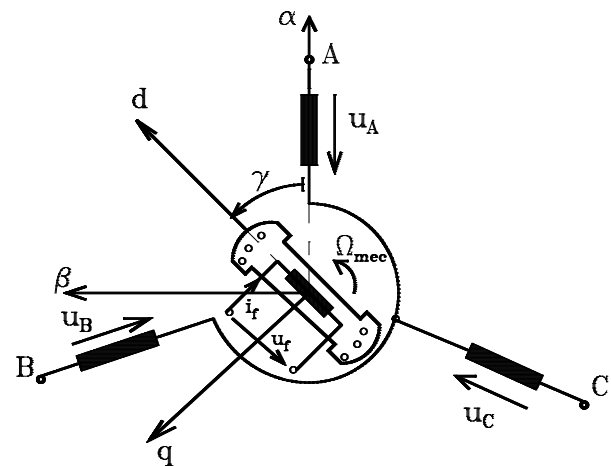

Fig. 4. Representation of windings and frame systems (α,β) and (d,q) of the synchronous generator

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

$$\Delta i_d = (2\,\Delta i_A \cdot \cos\gamma_0\,)/3 \; ; \; \Delta i_q = -(2\,\Delta i_A \cdot \sin\gamma_0\,)/3 \quad (7)$$

That 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:

$$\Delta \Psi_d = L_d'' \cdot \Delta i_d \; ; \; \Delta \Psi_q = L_q'' \cdot \Delta i_q \qquad (8)$$

Considering the recurrence relations between the coordinates (d, q) and (α, β) [24,27]:

$$\Delta i_d = \Delta i_\alpha \cdot \cos \gamma_0 + \Delta i_\beta \cdot \sin \gamma_0$$
$$\Delta i_q = -\Delta i_\alpha \cdot \sin \gamma_0 + \Delta i_\beta \cdot \cos \gamma_0 \qquad (9)$$

it can be hypothesized that these sudden variations Δi_d and Δi_q would be determined by some correspondent variations Δi_α and Δi_β (unknown, for the time being) of the currents flowing through the stator windings (α, β) of the equivalent machine.

Similarly, the fluxes' variations $\Delta \Psi_\alpha$ and $\Delta \Psi_\beta$ are determined:

$$\Delta \psi_\alpha = \Delta \psi_d \cdot \cos \gamma_0 - \Delta \psi_q \cdot \sin \gamma_0$$
$$\Delta \psi_\beta = \Delta \psi_d \cdot \sin \gamma_0 + \Delta \psi_q \cdot \cos \gamma_0 \qquad (10)$$

If relations (9) are substituted in (8), with the further results in (10), we obtain the dependencies among the fluxes' variations $\Delta \Psi_\alpha$, $\Delta \Psi_\beta$ and the corresponding currents' variations Δi_α, Δi_β:

$$\Delta \psi_\alpha = (L_d'' \cos^2 \gamma_0 + L_q'' \sin^2 \gamma_0)\Delta i_\alpha +$$
$$+ (L_d'' - L_q'') \sin \gamma_0 \cos \gamma_0 \Delta i_\beta \qquad (11)$$
$$\Delta \psi_\beta = (L_d'' - L_q'') \sin \gamma_0 \cos \gamma_0 \Delta i_\alpha +$$
$$+ (L_d'' \sin^2 \gamma_0 + L_q'' \cos^2 \gamma_0)\Delta i_\beta$$

With the supplementary notations:

$$L_x = (L_d'' + L_q'')/2$$
$$L_y = (L_d'' - L_q'')/2 \qquad (12)$$

equation (11) takes the form:

$$\Delta \psi_\alpha = (L_x + L_y \cos 2 \gamma_0)\Delta i_\alpha + L_y \sin 2 \gamma_0 \Delta i_\beta$$
$$\Delta \psi_\beta = L_y \sin 2 \gamma_0 \Delta i_\alpha + (L_x - L_y \cos 2 \gamma_0)\Delta i_\beta \qquad (13)$$

The fluxes' variations $\Delta \Psi_\alpha$ and $\Delta \Psi_\beta$ implicitly determine further voltage variations. These will result from the synchronous generator voltage equations in coordinates α, β:

$$\Delta u_\alpha = -R \cdot \Delta i_\alpha - \frac{d}{dt} \Delta \psi_\alpha$$
$$\Delta u_\beta = -R \cdot \Delta i_\beta - \frac{d}{dt} \Delta \psi_\beta \qquad (14)$$

or after substituting the expressions of $\Delta \Psi_\alpha$ and $\Delta \Psi_\beta$:

$$\Delta u_\alpha = -R\Delta i_\alpha - (L_x + L_y \cos 2 \gamma_0)\frac{d}{dt} \Delta i_\alpha - L_y \sin 2 \gamma_0 \frac{d}{dt} \Delta i_\beta \qquad (15)$$

$$\Delta u_\beta = -R\Delta i_\beta - L_y \sin 2 \gamma_0 \frac{d}{dt} \Delta i_\alpha - (L_x - L_y \cos 2 \gamma_0)\frac{d}{dt} \Delta i_\beta$$

Writing with capitals the operational Laplace images of voltages and currents, the system of equations (15) becomes:

$$\Delta U_\alpha = -\{R + (L_x + L_y \cos 2 \gamma_0)p\}\Delta I_\alpha - L_y \sin 2 \gamma_0 p\Delta I_\beta \qquad (16)$$
$$\Delta U_\beta = -L_y \sin 2 \gamma_0 p\Delta I_\alpha - \{R + (L_x - L_y \cos 2 \gamma_0)p\}\Delta I_\beta$$

Equations (16) ascertain, in a general case, the link between the current variations and voltage variations at the terminals of the windings α,β of the synchronous generator. In the context of some local restrictions, these equations can be simplified, both for short-circuit and load disconnection.

3.2 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'' [27-29]. 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 [28-30] this parameter is connected to L_q'' and $(L_d''+L_q'')/2$, whereas other studies [31-32] consider it equal to $(L_d'' L_q'')^{1/2}$ 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 [27], defined as:

$$L_{d.g.} = \frac{\Delta \psi_\alpha}{\Delta i_\alpha} \qquad (17)$$

Since in such processes [28] $u_\beta = 0$ or u_β = const., we obtain $\Delta u_\beta = 0$. If at the first moment the windings are considered as superconducting (R = 0), the restriction $\Delta u_\beta = 0$ substituted in equation (14.b) will lead to:

$$-\frac{d}{dt} \Delta \psi_\beta = 0 \Rightarrow \Delta \psi_\beta = const. = 0 \qquad (18)$$

From equation (13.b) it is obtained the recurrence relation:

$$\Delta i_\beta = -\frac{L_y \cdot \sin 2 \gamma_0}{L_x - L_y \cdot \cos 2 \gamma_0} \cdot \Delta i_\alpha \qquad (19)$$

which is used to determine the flux variation $\Delta \Psi_\alpha$:

$$\Delta \psi_\alpha = \frac{L_x^2 - L_y^2}{L_x - L_y \cdot \cos 2\gamma_0} \cdot \Delta i_\alpha \qquad (20)$$

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

$$L_{d.g.} = \frac{L_x^2 - L_y^2}{L_x - L_y \cdot \cos 2\gamma_0} \qquad (21)$$

With the notations (12) the dynamic inductance (21) can be written as the form:

$$L_{d.g.} = \frac{L_d'' \cdot L_q''}{L_d'' \cdot \sin^2 \gamma_0 + L_q'' \cdot \cos^2 \gamma_0} =$$
$$= \left\{ \frac{1}{L_q'' / \sin^2 \gamma_0} + \frac{1}{L_d'' / \cos^2 \gamma_0} \right\}^{-1} \qquad (22)$$

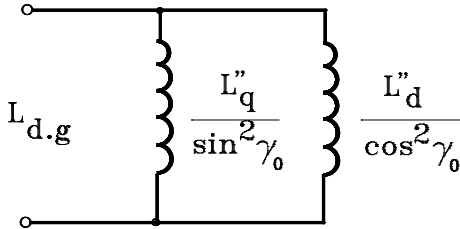The equivalent circuit corresponding to relation (22) is represented in Figure 5.

Figure 5. Equivalent circuit for dynamic inductance of synchronous generator

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 γ_0 at the perturbation moment. Referring to γ_0, the dynamic inductance takes distinct values for $0 \le \gamma_0 \le \pi$, 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:

$$L_{d.g.med} = \frac{1}{\pi} \int_0^\pi \frac{L_d'' \cdot L_q''}{L_d'' \cdot \sin^2 \gamma_0 + L_q'' \cdot \cos^2 \gamma_0} d\gamma_0 \quad (23)$$

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

$$L_{d.g.med} = \sqrt{L_d'' \cdot L_q''} \qquad (24)$$

Solely adopting this point of view the assumption emphasized in [24] takes a physical justification.

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

$$L_{d.g.ef} = \sqrt{\frac{1}{\pi} \int_0^\pi \left\{ \frac{L_d'' L_q''}{L_d'' \sin^2 \gamma_0 + L_q'' \cos^2 \gamma_0} \right\}^2 d\gamma_0} \quad (25)$$

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

$$L_{d.g.ef} = \left\{ \frac{L_d'' + L_q''}{2} \sqrt{L_d'' \cdot L_q''} \right\}^{1/2} \qquad (26)$$

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 ascertained the relations: $L_d'' < L_{d.g.ef} < L_{d.g.med} < (L_d'' + L_q'')/2 < L_q''$.

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_d''. 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:

$$L_g = \lambda_g \cdot L_d'' \qquad (27)$$

where λ_g is a sub-unit numerical factor.

Usually $\lambda_g = 0.6\text{-}0.85$ and it could vary from one generator to another.

3.3 First Phase Current Interruption
The initial conditions corresponding to the three-phase short-circuit are specified by $u_A(t)=u_B(t) = u_C(t)$. After the current interruption in phase A, the synchronous generator is passing for a short time in a two-phases short-circuit, with $u_B(t)= u_C(t)$. Calculation of voltage at the terminals of winding β:

$$u_\beta = \{ u_B - u_C \} / \sqrt{3} \qquad (28)$$

emphasizes that on whole perturbation duration $u_\beta=0$, and consequently $\Delta U_\beta=0$ as well.

Therefore, the current variations ΔI_α and ΔI_β are linked by the relation:

$$\Delta I_\beta = - \frac{L_y \cdot \sin 2\gamma_0 \cdot p}{R + (L_x - L_y \cdot \cos 2\gamma_0) \cdot p} \Delta I_\alpha \quad (29)$$

By substituting further the relation above in expression (16.a) we obtain:

$$\Delta U_\alpha = - \frac{R^2 + 2R \cdot L_x \cdot p + (L_x^2 - L_y^2) \cdot p^2}{R + (L_x - L_y \cdot \cos 2\gamma_0) \cdot p} \cdot \Delta I_\alpha \quad (30)$$

Equation (30) constitutes precisely the operational equation of the synchronous generator in the coordinates α,β 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 $u_{BC}=u_B-u_C$ remains actually unchanged, and also that $u_\beta = u_{BC}/\sqrt{3}$, 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 (12) the equation (30) we obtain the form:

$$\Delta U_\alpha = -\frac{(R+pL_d'')(R+pL_q'')}{(R+pL_d'')\sin^2\gamma_0+(R+pL_q'')\cos^2\gamma_0}\Delta I_\alpha \quad (31)$$

or

$$\Delta U_\alpha = -\Delta I_\alpha \frac{1}{\dfrac{1}{\dfrac{R}{\sin^2\gamma_0}+p\dfrac{L_q''}{\sin^2\gamma_0}}+\dfrac{1}{\dfrac{R}{\cos^2\gamma_0}+p\dfrac{L_d''}{\cos^2\gamma_0}}} \quad (32)$$

Since the coordinates α of voltages and currents are determined with the following relations:

$$u_\alpha = \frac{2}{3}\left(u_A - \frac{u_B+u_C}{2}\right) \; ; \; i_\alpha = \frac{2}{3}\left(i_A - \frac{i_B+i_C}{2}\right) \quad (33)$$

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

$$\Delta U_\alpha = 2/3\,\Delta U_A \; ; \; \Delta I_\alpha = 2/3\,\Delta I_A \quad (34)$$

Further equation (32) takes the form:

$$\Delta U_A = -\Delta I_A \left\{ \frac{1}{\dfrac{R}{\sin^2\gamma_0}+p\dfrac{L_q''}{\sin^2\gamma_0}}+\frac{1}{\dfrac{R}{\cos^2\gamma_0}+p\dfrac{L_d''}{\cos^2\gamma_0}} \right\}^{-1} \quad (35)$$

Equation (35) allows settling the simplified operational circuit, without considering the capacitance of the synchronous generator at the first phase interruption, as depicted in Figure 6.
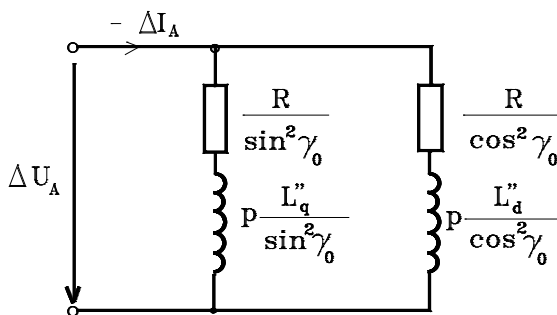

Figure 6. Simplified operational circuit of synchronous generator at first phase current interruption

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.

3.4 Synchronous Generator Operational Circuit at First Phase Current Interruption

Studies on synchronous generator windings over the interruption processes [27-30] 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 7), it is ascertained that through the stator winding A:

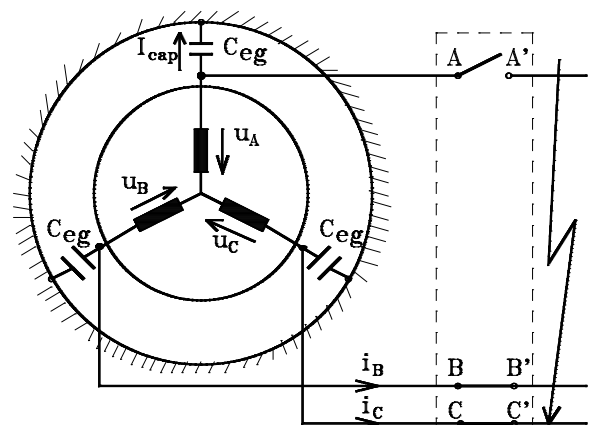$$\Delta I_A(p) = I_{cap}(p) - I_A(p) \quad (36)$$

Figure 7. Equivalent concentrated capacitances at first phase current interruption

Still, one could note that the capacitance presence will determine further the forming 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 [24,27]. 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 (27)) 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 (35) the inductances L_d'' and L_q'' are replaced by L_g, the resistance R is replaced by R_g, and we take into consideration relation (36), in which:

$$I_{cap} = p \cdot C_{eg} \cdot \Delta U_A \qquad (37)$$

the following results:

$$\Delta U_A = \left(p \cdot C_{eg} + \frac{1}{R_g + p \cdot L_g} \right)^{-1} \cdot I_A \qquad (38)$$

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 [27-30], as depicted in Figure 8, where:
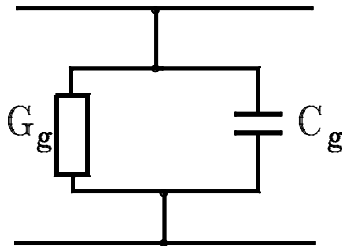

Figure 8. Equivalent parallel circuit
of the capacitor C_{eg}

$$G_g = G_0 + \omega \cdot C_{(max)} \cdot \sin \delta_h$$

$$C_g = C_{(max)} \cdot \cos \delta_h$$

where G_0 denotes the d.c. conductance; $C_{(max)}$ the apparent capacitance over the loading cycle (equal to Q_{max}/U_{max}); and δ_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 $\delta = \pi/2 - |\varphi_e|$ 1 is the total losses' angle and $tg\delta = G_g / \omega \cdot C_g$ 2 is the losses' factor, the following result:

$$G_g = \omega \cdot C_g \cdot tg\delta$$

$$G_g = I_{cap} \cdot \sin \delta / \Delta U_A \qquad (39)$$

$$C_g = I_{cap} \cdot \cos \delta / \Delta U_A$$

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

$$C_g = C_{eg} \; ; \quad G_g = \omega \cdot C_{eg} \cdot tg\delta \qquad (40)$$

Consequently, the operational circuit (38) becomes:

$$\Delta U_A(p) = \left\{ G_g + p \cdot C_g + \frac{1}{R_g + p \cdot L_g} \right\}^{-1} \cdot I_A(p) \quad (41)$$

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 (41) can be rewritten in the form:

$$\Delta U_A = \left\{ G_g + p \cdot C_g + \frac{1}{R_g + p \cdot L_g} \right\}^{-1} \cdot (-\Delta I_{Ab}) \quad (42)$$

In Figure 9 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.
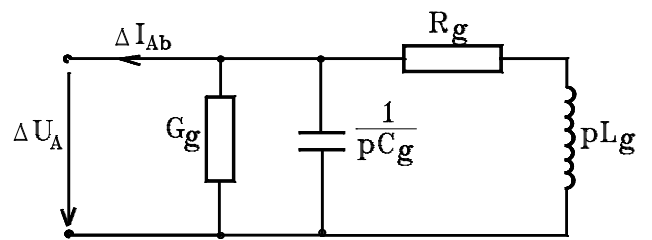

Figure 9. Operational circuit of synchronous
generator at first phase current interruption

4 Assessment of Concentrated Equivalent Parameters of Synchronous Generator Windings at Current Interruption Transient Processes

The method of operational symmetrical components has been applied here to determine the operational equations and configurations of the transient recovery voltage which appears at the generator circuit-breaker terminals after the interruption of a short-circuit fed by the synchronous generator. The TRV which appears after the interruption of a short-circuit fed by the synchronous generator may be considered as an oscillation with the oscillation factor and the rising rate (RR) of the TRV established by the electric parameters of synchronous generator: resistance, inductance and capacitance.

This assessment step is necessary but not sufficient for the modeling of TRV. That is, the structure of the operational impedances of the generator $Z_{g+}(p)$ and $Z_{g-}(p)$ must be assessed taking into consideration the concentrated equivalent parameters of the synchronous generator. This issue is not simple in a sustainable study, since during the interruption current transient processes the electromagnetic phenomena in the generator are complex, and interactions of the generator with the power electric network occur. Modeling the concentrated

equivalent parameters of the generator at perturbations caused by current interruption transient processes is imposed.

Studies on the synchronous generators stator windings during the transient processes caused by current interruptions have led to the hypothesis that they can be seen like long straight conductors [27-30]. Thus, the generator capacitance is mainly distributed between each winding and the ferromagnetic core, because both the capacitive coupling among the phase windings and the longitudinal capacitance (among winding turns) are very small and can be neglected. On the other hand, both the mutual inductance among the coils of proximate slots, and the inductance of the frontal terminals zone, can be neglected. Consequently, any phase winding can be seen as a chain of inductances without mutual coupling, having solely capacitances which are uniformly distributed to ground [29-30].

In order to enhance this knowledge, we consider an elementary section (with the length "dx") from the phase winding of a synchronous generator with the parameters (electric resistance R', inductance L', electric capacitance C' and electric conductance G') uniformly distributed.

If the conductance $G' = 0$ (assuming a winding with a perfect insulation) the section "dx" corresponds to the representation in Figure 10.
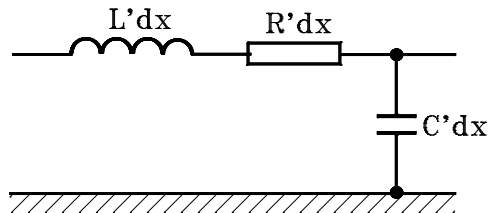

Fig. 10 Elementary section of a synchronous generator phase winding

On the entire length l, the synchronous generator phase winding (with perfect insulation) is made [31] from identical cells chain of inductances without mutual coupling, having only capacitances which are uniformly distributed to the ground, as in Figure 11.
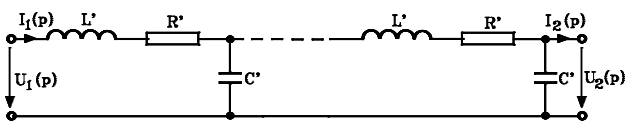

Fig. 11 Long straight conductors corresponding to the generator phase winding

The winding can be seen as a quadrupole, with the operational equation:

$$\begin{vmatrix} U_2(p) \\ I_2(p) \end{vmatrix} = \begin{vmatrix} ch(\gamma l) & Z_c \cdot sh(\gamma l) \\ \dfrac{1}{Z_c} \cdot sh(\gamma l) & ch(\gamma l) \end{vmatrix} \cdot \begin{vmatrix} U_1(p) \\ I_1(p) \end{vmatrix} \tag{43}$$

where

$$\gamma(p) = \sqrt{(R' + p \cdot L') \cdot (0 + p \cdot C')} =$$
$$= p \cdot \sqrt{L' \cdot C'} \cdot \sqrt{1 + \frac{R'}{p \cdot L'}} \tag{44}$$

which is the operational constant of propagation, and

$$Z_c = \sqrt{\frac{R' + p \cdot L'}{0 + p \cdot C'}} = \sqrt{\frac{L'}{C'}} \cdot \sqrt{1 + \frac{R'}{p \cdot L'}} \tag{45}$$

which represents the wave operational impedance (or the characteristic impedance). By developing in power series the radical and under the restraint of the first two terms, the expressions as before can be approximated by $\gamma(p) = \alpha + p \cdot \beta$, where the damping coefficient is $\alpha = \dfrac{R'}{2} \cdot \sqrt{\dfrac{C'}{L'}}$ and the phase constant is $\beta = \sqrt{L' \cdot C'}$. That is,

$$Z_c(p) = \sqrt{\frac{L'}{C'}} + \frac{R'}{2} \cdot \frac{1}{p \cdot \sqrt{L' \cdot C'}} \tag{46}$$

On the other hand, the concentrated equivalent parameters (and, mainly, the longitudinal capacitance C_g of a phase winding) are not defined in an absolute mode and they are dependent both on the stator windings connection and on the situation of the neutral point to the ground.

Further, in this sense, we consider the case of star (Y) connection of windings, with grounded neutral (U_1=0). We determine, as an original contribution, the concentrated equivalent parameters L_g, R_g and C_g of the equivalent configuration represented in Figure 12, based on certain conditions, linked to the analytical methods of conservation of the impedances, of the self frequencies and of the electrostatic energies, respectively.
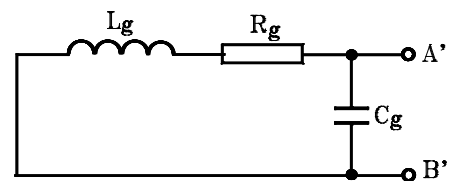

Fig. 12 Equivalent configuration with concentrated parameters

4.1 Method of Equal Impedances (or Equal Admittances)

This method is based on the identity of the impedances $Z_{A'B'}$ (at the terminals of the concentrated parameters equivalent scheme) and Z_{AB} (at the terminals of the line from the Figure 12, having a short-circuited terminal).

The long lines' equations, equivalent to the synchronous generator phase winding for $U_1=0$, are described by:

$$U_2(p) = Z_c \cdot I_1(p) \cdot sh\gamma l$$
$$I_2(p) = I_1(p) \cdot ch\gamma l \tag{47}$$

and, consequently,

$$Z_{AB}(p) = \frac{U_2(p)}{I_2(p)} = Z_c \cdot th\gamma l \text{ and } Y_{AB}(p) = \frac{cth\gamma l}{Z_c} \tag{48}$$

With equations (44) and (45), the ratio $\frac{\gamma(p)}{Z_c(p)} = p \cdot C'$ is achieved, resulting in

$$Z_c(p) = \frac{\gamma(p)}{p \cdot C'} \tag{49}$$

and

$$Z_{AB}(p) = \frac{1}{p \cdot C' \cdot l} \cdot \frac{\gamma(p) \cdot l}{cth\gamma l} = \frac{1}{Y_{AB}(p)} \tag{50}$$

But, the equivalent admittance at the terminals $A'B'$ of the representation in Figure 12 is:

$$Y_{A'B'} = p \cdot C_g + \frac{1}{R_g + p \cdot L_g} = \frac{p^2 \cdot L_g \cdot C_g + p \cdot C_g \cdot R_g + 1}{p \cdot L_g + R_g} \tag{51}$$

From the equality of the expressions of the two admittances, $Y_{A'B'}$ and Y_{AB}, we obtain the relation for C_g:

$$C_g = \frac{C' \cdot p \cdot (R_g + p \cdot L_g) - \gamma \cdot th\gamma l}{p \cdot (R_g + p \cdot L_g) \cdot \gamma \cdot th\gamma l} \tag{52}$$

Since both the resistance and the inductance interfere with the limitation of the short-circuit currents, their values are adopted as invariant in the two configurations, meaning that $R_g = R_{eg} (\approx l \cdot R')$ and $L_g = L_{eg} (\approx l \cdot L')$. Therefore, equation (52) can be rewritten as:

$$C_g = \frac{C' \cdot l \cdot p \cdot (R' + p \cdot L') - \gamma \cdot th\gamma l}{p \cdot (R' + p \cdot L') \cdot \gamma \cdot l \cdot th\gamma l} \tag{53}$$

or, taking into account equation (44),

$$C_g = C' \cdot l \cdot \frac{\gamma \cdot l - th\gamma l}{\gamma^2 \cdot l^2 \cdot th\gamma l} \tag{54}$$

Since for $|x| < \pi/2$ the function thx admits the development [24,27]:

$$thx = x - \frac{x^3}{3} + \frac{2x^5}{15} - \frac{17x^7}{315} + \ldots$$

and taking into account solely the first two terms, equation (54) becomes:

$$C_g = C' \cdot l' \cdot \frac{1/3}{1 - (1/3) \cdot \gamma^2 \cdot l^2} \tag{55}$$

At the limit, when $\gamma \cdot l \to 0$, the capacitance C_g has the tendency to attain the maximum:

$$C_g = \frac{C' \cdot l}{3} = \frac{C_{eg}}{3} = 0.33 \cdot C_{eg} \tag{56}$$

The long lines' equations, equivalent to the synchronous generator phase winding for $U_1=0$, are described by:

4.2 Method of Equal Self-Frequencies

The method is based on the identity of the self-frequencies corresponding to the two circuits (at the resonance).

With the complex variable $p = j \cdot \omega_0$, in the absence of the losses ($R' = 0$), the circuits admittances, at the resonance, will be zero. Thus, in the case of the line with distributed parameters, from equation (50) (with $p = j \cdot \omega_0$), we obtain:

$$j \cdot \omega_0 \cdot C' \cdot l \cdot \frac{cth\gamma l}{\gamma \cdot l} = 0 \tag{57}$$

or $\quad \cos j\gamma(j\omega_0) \cdot l = 0 \tag{58}$

Since $\gamma(j\omega_0) = j \cdot \omega_0 \cdot \sqrt{L' \cdot C'}$, from equation (58) we obtain

$$\omega_0 = \frac{\pi}{2 \cdot l \cdot \sqrt{L' \cdot C'}} \tag{59}$$

The self-pulsation of the concentrated parameters equivalent circuit is

$$\omega_{0g} = \frac{1}{\sqrt{L_g \cdot C_g}} \tag{60}$$

From the equality of the two self-pulsations:

$$\frac{1}{L_g \cdot C_g} = \frac{\pi^2}{4 \cdot L' \cdot l \cdot C' \cdot l} \tag{61}$$

under the assumption $L_g = L' \cdot l$, we obtain the equivalent capacitance value:

$$C_g = \frac{4}{\pi^2} \cdot (C' \cdot l) = 0.406 \cdot C_{eg} \tag{62}$$

where $C_{eg} = C' \cdot l$ it is the total capacitance distributed along the synchronous generator phase winding.

4.3 Method of Equal Electrostatic Energies

The starting point of the method is based on the statement that two equivalent circuits, for the same voltage amplitude, equally store electrostatic energies.

Thus, admitting a linear variation of the voltage along the winding (see Figure 13), with:

$$U_2 - U_1 = \Delta U \qquad (63)$$

into an elementary capacitance $C' = C/l$, situated at the distance x from the winding terminal, the stored electrostatic energy is $W_x = \frac{1}{2} \cdot C' \cdot U_x^2$, where

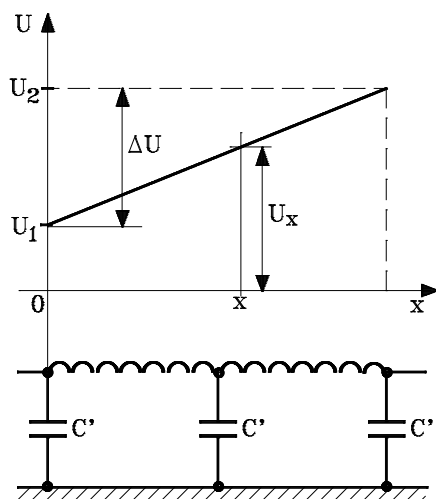$$U_x = U_1 + \frac{x}{l} \cdot \Delta U \qquad (64)$$

Fig. 13 Voltage variation along
a phase winding

The total energy stored in the entire winding capacitance is determined with

$$W = \int_0^l W_x \cdot dx = \frac{1}{2} \cdot C' \cdot l \cdot [U_1^2 + U_1 \cdot \Delta U + \frac{1}{3}(\Delta U)^2] \qquad (65)$$

Since $U_1 = U_2 - \Delta U$, equation (65) becomes

$$W = \frac{1}{2} \cdot U_2^2 \cdot (C' \cdot l) \cdot [1 - \frac{\Delta U}{U_2} + \frac{1}{3} \cdot (\frac{\Delta U}{U_2})^2] \qquad (66)$$

It is emphasized that the electrostatic energy stored in the concentrated capacitance C_g at the voltage U_2 is $\frac{1}{2} \cdot U_2^2 \cdot C_g$, and by identification with equation (66) we obtain

$$C_g = C' \cdot l \cdot [1 - \frac{\Delta U}{U_2} + \frac{1}{3} \cdot (\frac{\Delta U}{U_2})^2] \qquad (67)$$

In the case of the grounded windings, $U_1 = 0$ and $U_2 = \Delta U$. Consequently, from the expression (67) we find again that $C_g = \frac{1}{3} \cdot (C' \cdot l)$.

5 Conclusion

This article 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.

The method of operational symmetrical components has been 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.

Applying the method of operational symmetrical components to determine the TRV which appears after the interruption of a short-circuit fed by the synchronous generator represents an original contribution of the authors of this study. Modeling transient recovery voltage of circuits emphasizes aspects with direct implication on commutation equipment. Thus, the o.s.c. method can be applied at the poles of any breaker, for any eliminated fault type, if the network configuration and elements are known.

Further, these findings have been 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 the model of an industrial ecosystem. Thus, adopting the pattern of ideal synchronous machine and applying the overlapping principle and the coordinate transformation, we obtained the operational equations of synchronous generator at sudden load variations.

As another main conclusion the importance is highlighted of the components (α, β). They provide a useful physical point of view concerning the phase current interruption, highlighting the dualist view of industrial ecology, according to which the behavioral analysis of an industrial ecosystem can be performed in two distinct reference frames.

These findings represent a necessary but not sufficient step for TRV modeling. Further modeling the concentrated equivalent parameters of the generator at perturbations caused by current

interruption transient processes is achieved in this study through an approach based on sustainability concepts.

Thus, using the equal impedance and equal electrostatic energy methods we obtain for the synchronous generator phase winding equivalent capacitance C_g the value $0.330 \cdot C_{eg}$. Applying the equal self-frequency method results in the value $0.406 \cdot C_{eg}$ for C_g. We conclude that the value of the equivalent capacitance C_g of a synchronous generator phase winding (depending on the applied method) varies in the range of $0.330 \cdot C_{eg}$ to $0.406 \cdot C_{eg}$, and these findings should be taken into consideration for modeling the TRV on the basis of operational impedances of the synchronous generator during the interruption processes transient processes.

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