NEW CONTROL STRATEGY OF INRUSH TRANSIENT DURING TRANSFORMER ENERGIZATION AT TOULNUSTOUC HYDROPOWER PLANT USING A DOUBLE-BREAK 330-kV CIRCUIT BREAKER

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***Abstract* – This paper summarizes the results of an exhaustive investigation of inrush transients during the energization of generator step-up transformer (GSUT) at the Toulnustouc hydropower plant using a double-break 330-kV circuit breaker. The effect of pre-insertion resistors to suppress GSUT inrush transients was clearly demonstrated. Finally a new control strategy of synchronized switching was developed for double-break 330-kV circuit breakers as an economic alternative solution for the energization of GSUT at Toulnustouc.**

Keywords - Inrush Transients, Controlled Switching, Temporary Over-voltages (TOV), Circuit Breakers, Pre-insertion Resistors, Grading Capacitors, System Restoration.

I. INTRODUCTION.

By 2005, the Toulnustouc hydropower plant will be put in service in the North-Eastern part of the Hydro-Québec transmission system. This generating station will include two generator units of 13.8 kV – 292 MVA and two generator step-up transformers (GSUT) of 320-13.8 kV – 315 MVA, as illustrated in Fig. 1. The total generated power from Toulnustouc will be transferred through a double-circuit 53-km line to the 315-kV bus of the Micoua 735-315 kV substation where the power from the existing Manic-Outardes complex is also collected and injected to the Hydro-Québec 735-kV main grid. Since each generator unit at Toulnustouc is integrated through its own GSUT, there is no requirement for the implementation of 13.8-kV generator circuit breakers. Therefore, the Hydro-Québec standard 330-kV circuit breakers of two breaks per pole with grading capacitors will be used for the switching of 315-kV line as well as of GSUT. Furthermore, in order to supply the station auxiliary services from the 315-kV side and to maintain the flexibility of operation during system restoration, each GSUT at Toulnustouc has to be energized by the 330-kV circuit breaker. This paper summarizes the results of an exhaustive investigation of inrush transients during the energization of a GSUT at Toulnustouc using a double-break 330-kV circuit breaker. The two following system restoration scenarios were thoroughly analyzed:

- Energization of GSUT at Toulnustouc from 735-kV main grid via the Micoua 735-315 kV substation

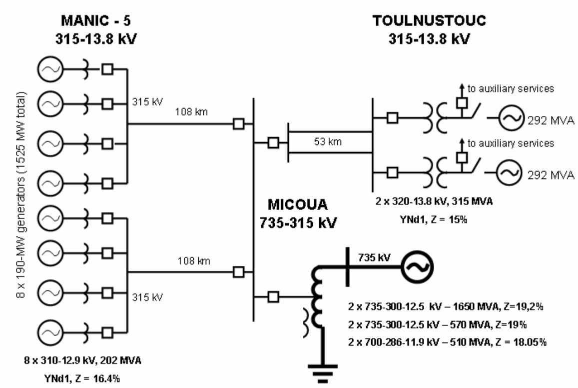


Fig. 1 Integration of the Toulnustouc 315-13.8 kV Hydropower Plant

- Energization of GSUT at Toulnustouc from a number of isolated generator units at the Manic-5 hydropower plant.

Finally, the effects of pre-insertion resistors and of controlled switching devices adapted for double-break 330-kV circuit breakers were also investigated.

II. ENERGIZATION OF GSUT AT TOULNUSTOUC FROM 735-kV MAIN GRID

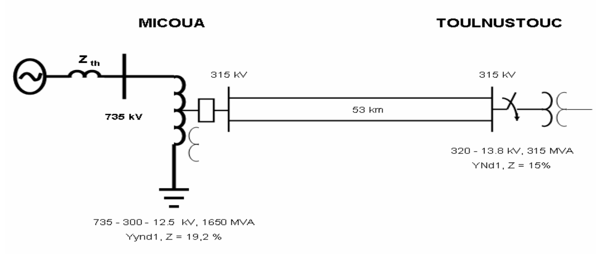
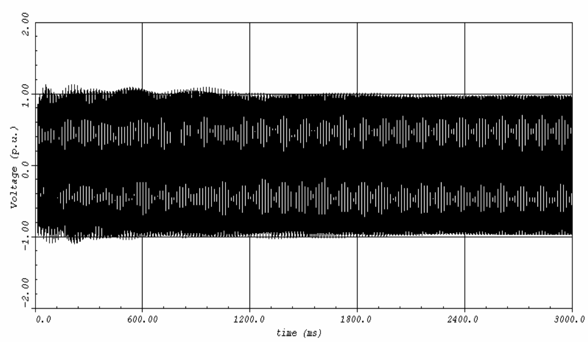


Fig. 2 Energization of a GSUT at Toulnustouc from the 735-kV Main Grid

In this system restoration scenario, the GSUT at Toulnustouc will be energized from the 735-kV main grid after the energization of the Micoua-Toulnustouc 315-kV line, as illustrated in Fig. 2. To obtain the maximum asymmetric condition, the GSUT was energized at zero voltage crossing on one of the three phases and the residual fluxes of +85 %, -85 % and 0% of the rated flux were set on the

GSUT three phases prior to the energization [1]. Furthermore, there was only one 735-300-12.5 kV – 1650 MVA transformer in service at the Micoua substation during system restoration. Fig. 3.a and 3.b show the typical results of voltages at Toulnustouc 315 kV and inrush currents during the energization of a GSUT from a 735-kV main grid having the short-circuit level of 25 kArms.

a) Voltages at Toulnustouc 315 kV



b) Inrush currents in GSUT

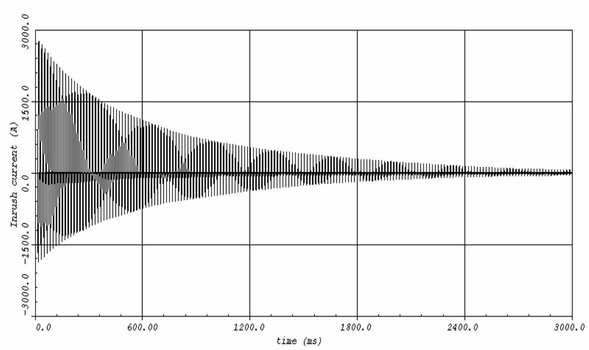


Fig. 3 Energization of a GSUT at Toulnustouc from the 735-kV main grid having the short-circuit level of 25 kArms

Since, transformer inrush currents are rich in harmonic contents, the frequency dependent network equivalent (FDNE) of a 735-kV main grid having the short-circuit level of 25 kArms, as illustrated in Fig. 4.a, 4.b, has also been used for the simulation of inrush transient due to the transformer energization at Toulnustouc. To obtain the parameters of this FNDE, the frequency scan of the Thévenin impedance Z(f) = R(f) + j X(f), which is seen at Micoua 735-kV bus bar without the presence of any 735-kV transformers in the substation, was first performed for the entire Hydro-Québec 735-kV main grid. The FNDE parameters R_n, L_n, C_n, as shown in the Table I, were then obtained by using the following formulas [2]:

$$R_n = |Z(f_{n\text{-}Xzero})| \text{ (in } \Omega) \quad (1)$$

$$L_n = R_n(f_{n\text{-}Xmin} - f_{n\text{-}Xmax}) / (2\pi . f_{n\text{-}Xmin} . f_{n\text{-}Xmax}) \text{ (in H)} \quad (2)$$

$$C_n = (k_n L_n)^{-1} \text{ (in F)} \quad (3)$$

$$k_n = 4\pi^2 (f_{n\text{-}Xmin} . f_{n\text{-}Xmax}) \quad (4)$$

where for the n^{th} pole of Z(f):

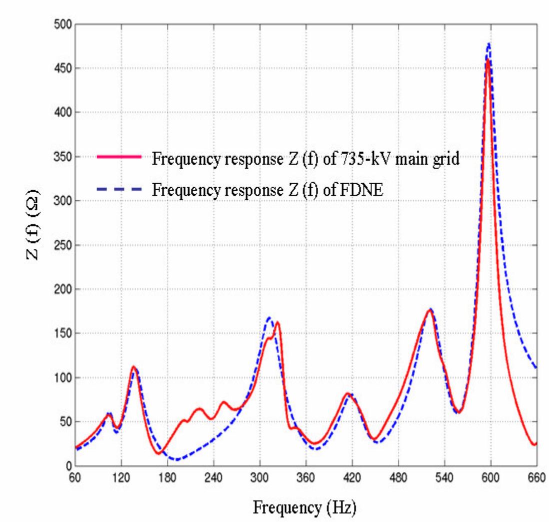
$f_{n\text{-}Xmax}$: the frequency, at which the value of X(f) is maximum inductive

$f_{n\text{-}Xmin}$: the frequency, at which the value of X(f) is minimum capacitive

$f_{n\text{-}Xzero}$: the frequency, at which the value of X(f) is zero

The simulation results, as illustrated in Fig. 5.a and 5.b, show very little impact of the 735-kV FDNE on the inrush transient during transformer energization at Toulnustouc. Indeed, the effect of the 735-kV FDNE was somehow hidden by the presence of the 735-300-12.5 kV transformer at the Micoua substation. In general, for the short-circuit levels of the Thévenin equivalent at Micoua 735 kV varying between 5 kArms and 40 kArms, there is no severe overvoltage observed during the energization of GSUT at Toulnustouc although the maximum inrush current reaches approximately 3000 Apeak and slowly decays over a period of 3 s. These voltages and currents are tolerable for the GSUT and other 315-kV equipment. Therefore, no remedy measure would be necessary for this system restoration scenario.

a) Frequency responses of 735-kV main grid and of FDNE



b) FDNE of 735-kV main grid

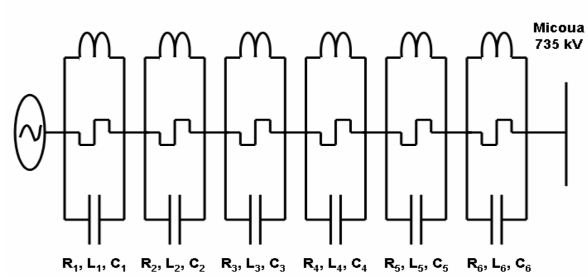
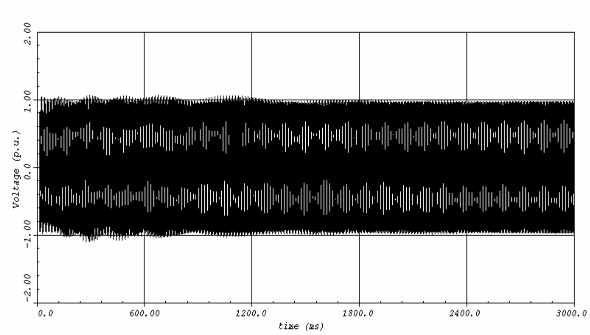


Fig. 4 Frequency dependent network equivalent (FDNE) of 735-kV main grid

Table I Parameters of frequency dependent network equivalent

	R (Ω)	L (mH)	C (μF)
R_1, L_1, C_1	36.66	5.76	385.83
R_2, L_2, C_2	106.25	16.91	76.54
R_3, L_3, C_3	162.50	7.53	34.13
R_4, L_4, C_4	70.31	1.90	75.33
R_5, L_5, C_5	165.62	3.27	28.33
R_6, L_6, C_6	459.38	3.76	18.97

a) Voltages at Toulnustouc 315 kV



b) Inrush currents in GSUT

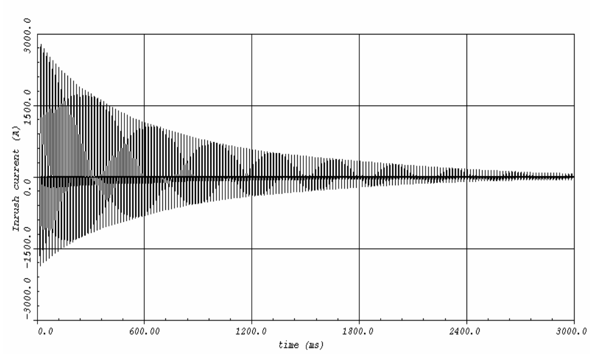


Fig. 5 Energization of a GSUT at Toulnustouc from the 735-kV main grid with FDNE having the short-circuit level of 25 kArms

III. Energization of GSUT at Toulnustouc from Manic-5

In this system restoration scenario, the GSUT at Toulnustouc will be energized from a number of isolated generator units at Manic-5 after the energization of Manic-5 – Micoua – Toulnustouc 315-kV lines, as illustrated in Fig. 6. The number of isolated generators at Manic-5 varies between 1 and 8 units. For the cases with more than 4 generator units at Manic-5, the second 315-kV line Manic-5 – Micoua was energized. Again, to obtain the maximum asymmetric condition, the GSUT was energized at zero voltage crossing on one of the three phases and the residual fluxes of +85 %, -85 % and 0% of the rated flux were set on the GSUT three phases prior to the energization.

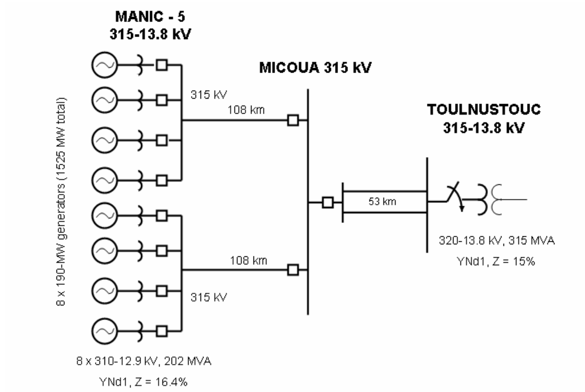
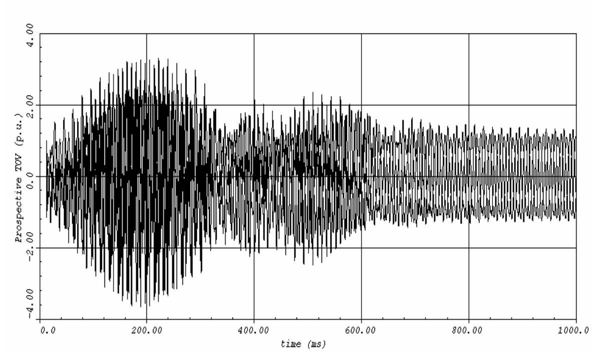


Fig. 6 Energization of a GSUT at Toulnustouc from a number of isolated generator units at Manic 5

Simulation results indicated that severe temporary overvoltages (TOV) and inrush currents appeared during the energization of a GSUT at Toulnustouc. For the case with only one generator unit in service at Manic-5, prospective TOV (without surge arrester) higher than 2.0 p.u. were observed over a period of 500 ms, as illustrated in Fig. 7.a. The maximum inrush current reached 1800 Apeak, as shown in Fig. 7.b. These TOV are harmful to the GSUT and to other 315-kV equipment. Therefore, remedy measures should be implemented to suppress these TOV during GSUT energization.

a) Prospective TOV at Toulnustouc 315 kV without surge arrester



b) Inrush current in GSUT

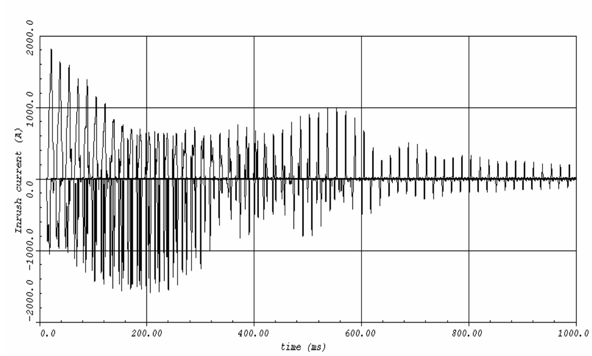


Fig. 7 Energization of a GSUT at Toulnustouc from Manic-5 with one isolated generator unit in service

IV. Effect of Pre-insertion Resistors

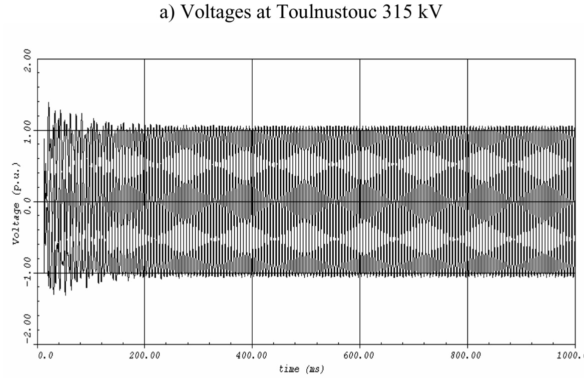
From the previous scenario, severe TOV appeared during the energization of a GSUT at Toulnustouc from a number of isolated generator units at Manic-5. The effect of pre-insertion resistors on 330-kV circuit breakers to suppress these inrush transients has been investigated. A range of pre-insertion resistors from 600 to 1200 Ω has been analyzed for the case of GSUT energization at Toulnustouc from one isolated generator unit at Manic-5. The insertion time was varied between 8 ms and 16 ms. Simulation results, as summarized in Table II, indicate that the pre-insertion resistor of 1000 Ω with a minimum insertion time of 12 ms would allow to suppress inrush transient during the worst condition of GSUT energization at Toulnustouc. Fig. 8 shows the typical simulation result of inrush transient with a pre-insertion resistor of 1000Ω -12 ms.

Table II Effect of pre-insertion resistors – GSUT energization at Toulnustouc from one isolated generator unit at Manic-5

R pre-insertion	Insertion time				
	8 ms	10 ms	12 ms	14 ms	16 ms
600 Ω	XXX	XXX	XXX	XXX	XXX
800 Ω	XXX	XXX	XXX	OK	OK
1000 Ω	XXX	XXX	OK	OK	OK
1200 Ω	XXX	XXX	OK	OK	OK

XXX = Severe TOV condition; OK = Acceptable transient

a) Voltages at Toulnustouc 315 kV



b) Inrush currents in GSUT

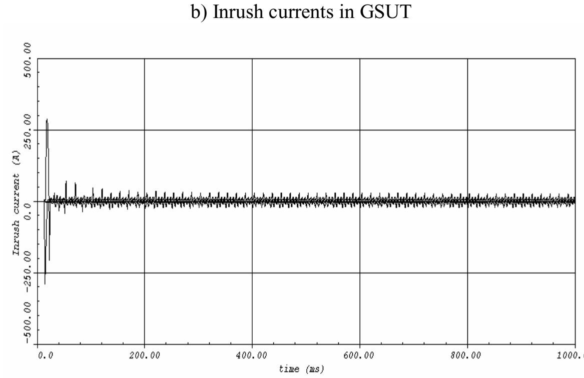


Fig. 8 Energization of a GSUT at Toulnustouc from Manic-5 with one isolated generator unit in service – 1000 Ω - 12 ms

V. Transformer Controlled Switching

The transformer controlled switching taking into account the measured residual flux was first introduced in Hydro-Québec transmission system with the application on single-break 330-kV circuit breakers at the Sainte Marguerite 3 (SM-3) gas-insulated substation (GIS) [3]. The success of the field test campaign at SM-3 has promoted the use of this technique as an economic and reliable alternative for pre-insertion resistors to control inrush transients at Toulnustouc hydropower plant.

A. Control Strategy for Transformer Switching

The closing control strategy for the three phases of the circuit breaker is described as follow:

- The phase with the highest measured residual flux (absolute value) is first energized at the angle α after a reference voltage zero crossing where the voltage slop is in opposite polarity with that of the measured residual flux. The angle α is calculated using the following formula:

$$a = \arccos\left(\frac{\phi_r\sqrt{3}}{V\sqrt{2}}\omega\right) \quad \text{(in degree)} \qquad (5)$$

  Where V is the applied line-to-line voltage in V rms, ϕ_r is the magnitude of the measured residual flux in Weber and $\omega = 2\pi$ f.

- After n half-cycles from the same reference voltage zero crossing, the two other phases are energized at the same instant. The n half-cycle delay is needed to reduce the flux asymmetry in these two later phases. According to simulations and field tests, a time delay of 4 ½ cycles (n=9) will give satisfactory results for most practical cases.

B. Effect of Grading Capacitors on Residual Flux.

According to the above described control strategy, the magnitude of residual flux in the transformer and the waveform of system power frequency voltage are the main parameters to determine the optimal instants for transformer energization.

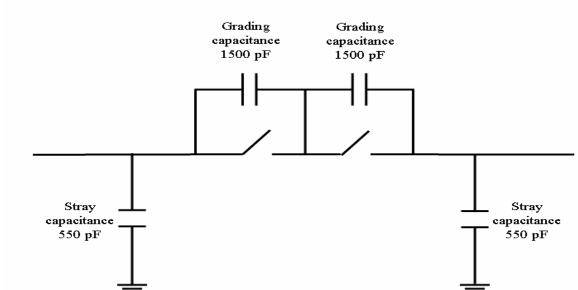


Fig. 9 Double-Break 330-kV Circuit Breaker for the Energization of GSUT at Toulnustouc

Moreover, double-break 330-kV circuit breakers equipped with grading capacitors of typical 1500 pF/ break, as illustrated in Fig. 9, will be used for the energization of GSUT at Toulnustouc. These grading capacitors together with the stray capacitances of bus bars and GSUT induce a power frequency voltage on the GSUT after the opening of the circuit breaker. The ranges of grading capacitors from 1500 pF to 7500 pF and of stray capacitances from 550 pF to 6000 pF have been used to analyze their effect on the residual flux in the GSUT following a de-energization. Simulation results, summarized in Fig. 10, show the variation of residual fluxes obtained with the stray capacitance of 550 pF. The presence of grading capacitors tends to decrease the residual flux in GSUT after de-energization. However, the dc flux components are still predominant. Therefore, the measurement of dc residual fluxes is still necessary to control the optimal instants for GSUT energization.

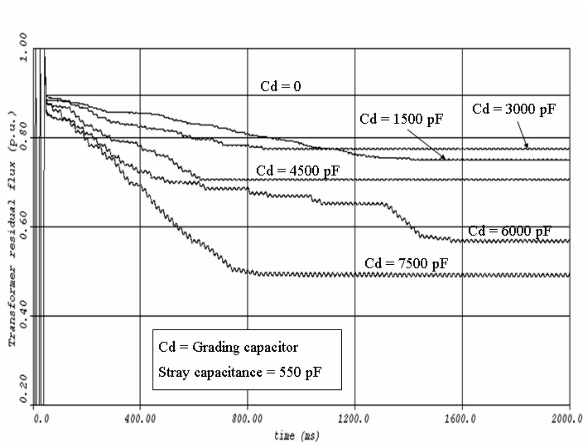


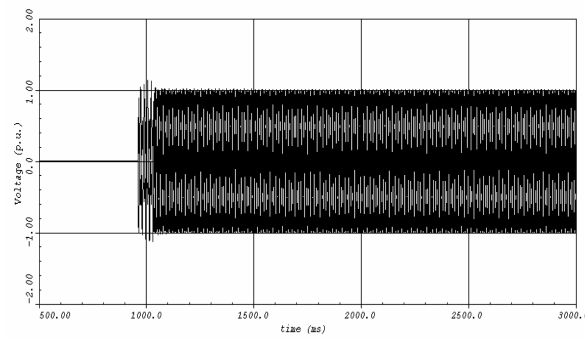
Fig. 10 Effect of Grading Capacitor on Residual Flux in GSUT

C. Controlled Switching of GSUT at Toulnustouc

The above mentioned control strategy was applied for the worst case scenario of GSUT energization at Toulnustouc from one isolated generator unit at Manic-5. The simulation results, as illustrated in Fig. 11.a and 11.b, show that with the optimal closing instants derived from this control strategy for the three phases of GSUT, inrush transients are completely attenuated.

Furthermore, to verify the robustness of this control strategy for double-break circuit breakers, 100 statistical energizations including Gaussian distributed closing errors of ± 1ms around the optimal closing instant for each phase, were performed. Simulation results, as illustrated in Fig. 12.a and 12.b, indicate that the worst inrush transients due to closing errors of double-break circuit breakers are still well controlled.

a) Voltages at Toulnustouc 315 kV



b) Inrush currents in GSUT

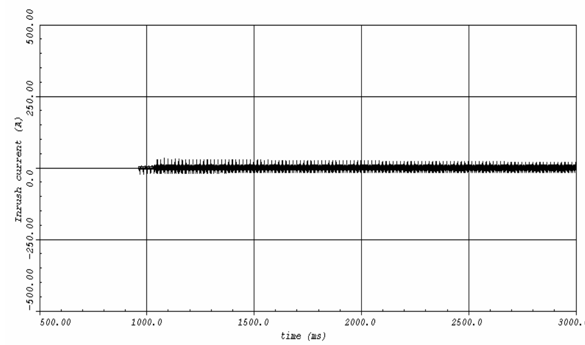
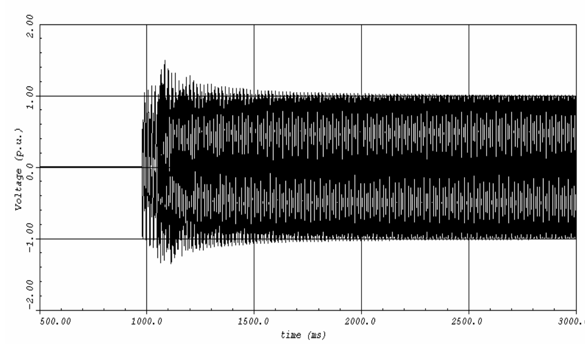


Fig. 11 Energization of a GSUT at Toulnustouc from Manic-5 with one isolated generator unit in service – with optimal closing instants

a) Voltages at Toulnustouc 315 kV



b) Inrush currents in GSUT

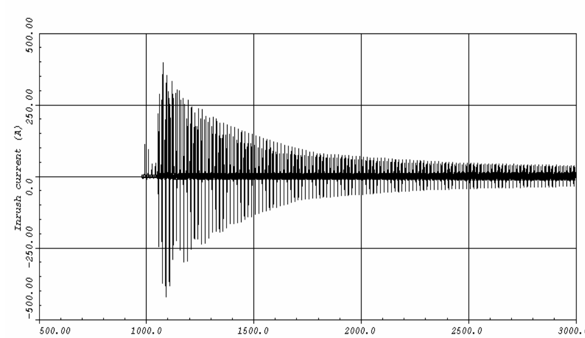


Fig. 12 Worst inrush transients due to Gaussian distributed closing errors of ±1 ms around the optimal closing instant for each phase.

VI. Conclusions

An exhaustive investigation of inrush transients during the energization of GSUT at Toulnustouc has been performed. In light of this study results the following main conclusions could be drawn:

- There is no harmful TOV during the energization of GSUT at Toulnustouc from the 735-kV main grid via the Micoua 735-315 kV substation.
- Severe TOV would appear during the energization of GSUT at Toulnustouc from a number of isolated generator units at Manic-5
- The pre-insertion resistors of 1000 Ω - 12 ms on double-break 330-kV circuit breakers would allow to suppress inrush transients during the energization of GSUT at Toulnustouc from a number of isolated generator units at Manic-5
- As an economic and reliable alternative for pre-insertion resistors, the transformer controlled switching using the measured residual flux could be applied on double-break 330-kV circuit breakers at Toulnustouc.

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