Energization of two transformers in series through long lines: Correlation between fluxes in both transformers, and determination of the efficiency of palliative solutions

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Abstract--The energization of power transformers following a complete or partial collapse of the system is an important issue. This paper describes a method for the modeling of the electric network between the source and a target transformer, when two transformers are involved, with a correlation between fluxes in both equipment. This method has been applied for the energization of an auxiliary transformer via a step-transformer.

Secondly, as those transformer energizations may lead those severe stresses, different palliative solutions have been addressed, including solutions using the Network capabilities, and also solutions related to circuit-breakers and surge arresters.

Keywords: Power restoration, transformer energization, modeling, harmonics, residual fluxes, temporary overvoltages, ferroresonance.

I. Nomenclature

$C_{\varphi/t}$:	phase-to-ground capacitance of the overhead lines	(F)
φ_n :	nominal flux in the target transformer	(Wb)
φ_{rA} :	residual flux in limb A	(Wb)
φ_{rB} :	residual flux in limb B	(Wb)
φ_{rC} :	residual flux in limb C	(Wb)
K :	factor taking into account the accuracy of the calculation	
$L(\varphi)$:	magnetization inductance including saturation, φ being the flux in a limb.	(H)
L_{l1} :	leakage inductance of the primary winding	(H)
L_{l2} :	leakage inductance for the secondary winding	(H)
L_{sat} :	last slope of the saturation flux-current curve of the target transformer	(H)
R_{Cu1} :	electric resistance of the primary circuit	(Ω)
R_{Cu2} :	electric resistance of the secondary circuit	(Ω)
R_{Fe} :	resistance describing the core losses	(Ω)
S_N :	rated power of the target transformer	(VA)
U_N :	nominal voltage of the EHV network	(V)
T''_d :	sub-transient time constant of the generator	(s)
X''_d :	sub-subtransient reactance in the d axis of the generator	(H)
V_{iY} :	phase-to-ground voltage of phase *i* at the star side of the transformer (i=1, 2, 3)	(V)
V_{iD} :	phase-to-ground voltage at *i* phase of the delta side of the transformer (i=1, 2, 3)	(V)
V_{ijD} :	phase-to-phase voltage between phase *i* and *j* at the delta side of the transformer (i=1, 2, 3)	(V)
M :	correlation matrix between fluxes in the step-up and auxiliary transformer	
α:	voltage ratio of the step-up transformer	

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II. Introduction

The energization of power transformers, and especially the auxiliary transformers of thermal power plants after a black-out may be an important issue [1]. It can lead to high overvoltages and currents [2], harmonic phenomena being involved, and also in some cases to ferroresonance conditions [3]. A methodology is described, especially when two transformers are involved, with a correlation between residual fluxes in both equipment.

III. Description of the methodology

A. General considerations

In this first part, the methodology is described, including the modeling of the network under harmonic conditions. In those cases related to power system restoration, the electrical network is described by the source generator, the lines and substations between this generator and the target transformer which has to be energized. In the following, a detailed description is performed in the case of a 900 MW generator, located in the South-West of France, the 58 MVA 20 kV/6.8 kV auxiliary transformer (named "AT" in the following) being energized, through a 1080 MVA 20 kV/400 kV step-up (named "SU") transformer via a 400 kV double-circuit line having a length of 180 km. This network is shown in figure 1.

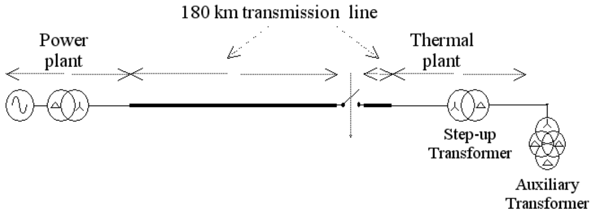

Figure 1 : Description of the 400 kV network

The circuit-breaker from which the transformer is energized is located in the substation of the thermal plant, 10 km away from the target transformer.
Zinc-oxide surge arresters having a rated voltage of 360 kV and located at the entrance of the main substations have also been represented.

B. Description of the modeling of the network

The equipments of the network have been modeled under the phenomena being involved [4][5] as follows:

- the generator, represented by a sinusoidal voltage source behind its subtransient reactance X''_d and the damping derived from the time constant T''_d, those parameters being given by the manufacturer. However, an accuracy of 15 % is taken on the X''_d value, attributed mostly to the accuracy of the measurements made on it, and also to the modeling of this equipment; the other reactances like the transient reactance have being neglected.
- the generator step-up transformer, modeled by a three-phase transformer where the leakage reactances, the copper and core losses and the saturation are taken into account. The delta-wye coupling is represented with its grounding reactance and its dedicated surge arrester. Resistance values have been increased in order to take into account the eddy currents and the skin effects :

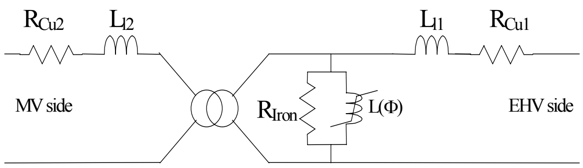

Figure 2 : Description of the transformer diagram (one phase).

- the zinc oxide surge arresters, having a rated voltage of 360 kV_{RMS} are represented by their non-linear resistance [6].
- the overhead lines are described by PI cells, the R, L, C parameters being derived from the electrical and geometrical parameters given by the Transportation Division of EDF using an auxiliary routine of the EMTP program. The number of PI cells has been chosen to 10 in order to represent correctly its exact impedance under the fifth harmonic which is the resonance frequency of this network (see figure 3); this model is especially adapted for the phenomena considered here, temporary overvoltages with an harmonic content; the skin effect has also been calculated at that frequency.

Since the sag of the line may vary along its entire length, an accuracy of 5 %, in accordance with the Transportation Division, has been considered for the phase-to-ground capacitances $C_{\varphi/t}$.

- the corona effect affecting the overhead lines is also represented, by non-linear resistances, inserted along the PI cells. Their parameters describing the losses are derived from the ratio between the electrical field generated by the wires and the Peek's critical field.
- the target step-up and auxiliary transformers are modeled like the previous one, except that the hysteretic characteristic is taken into account. The saturation is built from the voltage-current curve [3] given by the manufacturer. The parameter L_{sat}, describing the slope of this curve under high saturated conditions, is fixed at 0.4 pu* for the step-up transformer and to 0.1 pu for the auxiliary transformer.

*Note: The L_{sat} in p.u. is derived from the one in Henry by the following expression :

$$L_{sat}(pu) = L_{sat}(H)\frac{S_N \omega}{U_N^2}$$

In fact, these values correspond to the most conservative ones within the 20% accuracy range provided by manufacturer in order to take into account the fact that the value is not completely well defined, the transformer being tested only under low saturation conditions.

A frequency scan has then been performed with the EMTP program on the complete network, as shown below, figure 3 describing the direct impedance; in that case, a three-phase current source replaces the saturation part of the target transformer in order to get the equivalent impedance of the upstream network :

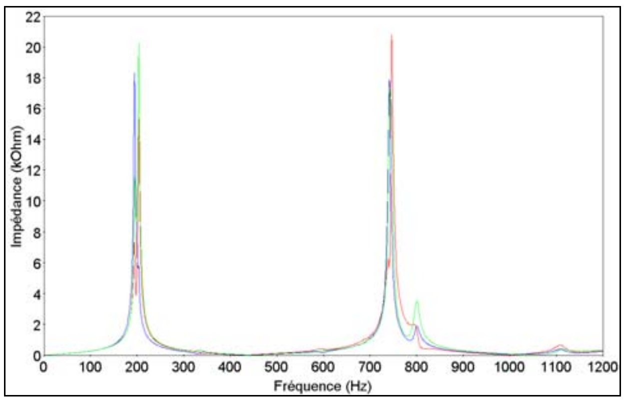

Figure 3 : Direct impedance versus frequency for the 400kV network.

It shows a resonance frequency close to the fourth harmonic at 200 Hz, the zero impedance being characterized by a frequency of 455 Hz.

Initial conditions, which may have a strong impact on the amplitude of the overvoltages have also been assessed, which is discussed in the following paragraph.

C. Hypothesis concerning the initial conditions for simulations purposes

The initial conditions concerned when energizing the target transformer are :

- the closing instants of the circuit breaker which operates,
- the residual fluxes circulating in the core of transformers before their energization.

In that aim, the following considerations have been taken into account.

Initial conditions associated to the circuit-breaker

The closing instant of pole A may occur at any time on the sinusoidal voltage according to a uniform distribution. The other two poles (phases B and C) follow the pole A according to a Gaussian distribution, which is centered on the closing instant of the pole A and characterized by its standard deviation, σ, which is considered for this breaker to be equal to 20 ms.

Initial conditions associated to residual fluxes circulating in step-up and auxiliary transformers

We have assumed that the residual fluxes inside the transformers, φ_{rj}, follow a uniform distribution and may reach an absolute value φ_{max} equal to 80 % of the nominal flux φ_n, φ_{rj} having a positive or negative value. The sum of the fluxes in the three phases vanishes to zero and a symmetry is considered (see table 1). These assumptions are consecutive to the type of the magnetic core (shell-type) and the delta connection at the 6.8 kV secondary side.

TABLE 1 : Residual flux patterns

φ_{rA}	φ_{rB}	φ_{rC}
φ	$-\varphi/2$	$-\varphi/2$
φ	$-\varphi$	0
$-\varphi/2$	φ	$-\varphi/2$
0	φ	$-\varphi$

The parameter φ varies from $-\varphi_{max}$ to $+\varphi_{max}$ with a step of $\varphi_{max}/2$, thus taking the following five values: $-0.8\cdot\varphi_n$, $-0.4\cdot\varphi_n$, 0, $0.4\cdot\varphi_n$, $0.8\cdot\varphi_n$. If one removes redundant occurrences, combination of these 5 values with the 4 residual patterns of Table 1 leads to 17 residual flux occurrences.

IV. CORRELATION BETWEEN FLUXES IN BOTH TRANSFORMERS BEING ENERGIZED

Since there is no circuit breaker between the two transformers of the thermal plant (step-up and auxiliary transformers) (see Figure 1), they are subjected to the same voltage, except for the transformer ratio and the phase shift. Thus, as the flux in a transformer is a function of the voltage, their residual fluxes are not independent but linked.

Because saturation branches showed in Figure 2 are located at the star side of both transformers, we need to calculate the relationship between phase voltages at both sides of the step-up transformer. Assuming that the coupling of this transformer is Ynd11, in balanced steady state conditions, phase to ground voltages in pu at both high and low voltage sides are the following:

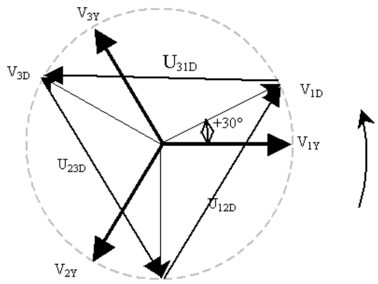

Figure 4 : Voltage phasors at both sides of the step-up transformer

These relations between phase voltages at both sides can be written as:

$$\begin{bmatrix} V_{1Y} \\ V_{2Y} \\ V_{3Y} \end{bmatrix} = \frac{1}{\alpha \cdot \sqrt{3}} \cdot [M] \cdot \begin{bmatrix} V_{1D} \\ V_{2D} \\ V_{3D} \end{bmatrix}$$

with :

$$[M] = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

Assuming that the flux in the step-up transformer is equal to the integral of phase-to-ground voltage at the 400 kV side (V_{iY}) and that the flux in the auxiliary target transformer is equal to the integral of phase-to-ground voltage at the 20 kV side (V_{iD}), we can state that:

$$\begin{bmatrix} \varphi_{rA,SU} \\ \varphi_{rB,SU} \\ \varphi_{rC,SU} \end{bmatrix} = \frac{1}{\alpha \cdot \sqrt{3}} \cdot [M] \cdot \begin{bmatrix} \varphi_{rA,AT} \\ \varphi_{rB,AT} \\ \varphi_{rC,AT} \end{bmatrix}$$

Where $\varphi_{rj,SU}$ is the residual flux in the step-up transformer and $\varphi_{rj,AT}$ is the residual flux in the auxiliary transformer.

This correlation matrix, M, cannot be inverted. This is due to the fact that three phase-to-phase voltages at the delta side do not determine three phase-to-ground voltages, unless the system is supposed to be balanced (that is, $V_{1Y}+V_{2Y}+V_{3Y}=0$). Though, the assumption that the sum of the three fluxes vanishes to zero ($\varphi_{rA,AT}+\varphi_{rB,AT}+\varphi_{rC,AT}=0$) is enough to obtain an invertible matrix. From this method, we derive the following alternative relationship:

$$\begin{bmatrix} \varphi_{rA,SU} \\ \varphi_{rB,SU} \\ \varphi_{rC,SU} \end{bmatrix} = \frac{1}{\alpha \cdot \sqrt{3}} [M'] \cdot \begin{bmatrix} \varphi_{rA,AT} \\ \varphi_{rB,AT} \\ \varphi_{rC,AT} \end{bmatrix} \quad [1]$$

with:

$$M' = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 1 & 0 & 2 \end{bmatrix}$$

This alternative matrix, M', can now be inverted and thus one can state the inverse relationship between fluxes:

$$\begin{bmatrix} \varphi_{rA,AT} \\ \varphi_{rB,AT} \\ \varphi_{rC,AT} \end{bmatrix} = \sqrt{3} \cdot \alpha \cdot [M']^{-1} \cdot \begin{bmatrix} \varphi_{rA,SU} \\ \varphi_{rB,SU} \\ \varphi_{rC,SU} \end{bmatrix} \quad [2]$$

Given these relations, we consider, on one hand, that the residual fluxes at the step-up transformer take the 17 occurrences of §2.3.2, equation [2] providing the 17 correlated occurrences at the auxiliary transformer; on the other hand, that the residual fluxes at the auxiliary transformer take also the 17 occurrences of §2.3.2, equation [1] providing then the 17 correlated occurrences at the step-up transformer. The removal of the redundant occurrences leads to 33 residual flux occurrences.

V. Calculation of the stresses on the target transformers (step-up and auxiliary transformer)

EMTP (EMTP 3.1 version, developed by the DCG) simulations have been performed, considering 5 occurrences of the parameters X''_d and $C_{\varphi/t}$, according to the accuracy on their values (see §2.2).

A scan of the initial conditions with the EMTP program has also been performed (1700 simulations) in order to determine the amplitude of the overvoltages, considering 33 occurences for the residual fluxes (§3) and 100 circuit-breaker switchings per occurence.

In fact, the step-up transformer is the most stressed one, and not the auxiliary transformer, as this last one has a withstand voltage higher compared to the step-up transformer, considering that the insulation thickness per kV will be thicker for lower voltage.

That is why we consider mainly the stresses applied to the step-up transformer, in p.u. unit values.

They reach a value of 1.49 p.u.* (phase to phase) and 1.78 p.u (phase to earth), this last value being the most critical one concerning the stresses on the internal insulation.

Note: 1 p.u.* = 342 kV for the phase to ground voltage.

Temporary harmonic phenomena at the SU transformer in the most severe case are described by the figure 4 below :

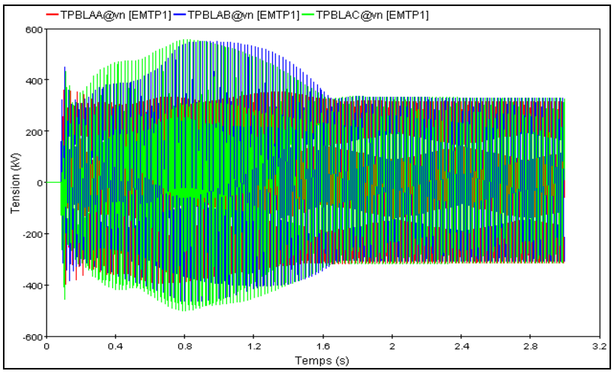

Figure 5 : Temporary harmonic overvoltages

Those values are compared to the withstand voltage of the insulation [7] given by the manufacturer, including the security coefficients derived from the IEC standard 71.1 for insulation coordination:

TABLE 2 : Values of security coefficients

	Phase-to-ground voltage	Phase-to-phase voltage
K	1.02	1.05

From simulation results, the withstand voltage of the transformer may be reached in some cases, implying the opportunity to perform partial on site tests, in order to assess the frequency of the network, and also palliative solutions in order to damp the overvoltages in the most severe cases.

Those tests and the calculation of the initial conditions associated to them are described in the following chapter.

VI. Description of the on-site measurements; determination of the initial conditions and the resonance frequency of the network

A. *On site tests*

On site tests have been performed by the Technical Transportation Division of EDF named DTG, on the energization of open ended lines. An acquisition system has been installed in the substations located at both ends, especially at the circuit breaker location. Phase-to-ground voltages have been measured from the on site dividers i.e. the voltage and current transformers. All the measurements have been digitized at the sampling rate of 400 Hz, stored and processed using the Matlab software.

B. *Determination of the resonance frequency of the upstream network*

The resonance frequency of the network has been computed by the mean of a Fourier analysis triggered immediately after the energization, and obtained from the measured phase-to-ground voltages.

Its spectrum shows, in addition to the 50 Hz, another measured peak value centered at 228 Hz (non harmonic),

which is consecutive to the excitation of the resonance of this network by those currents when the circuit breaker operates.
By this mean, the resonance frequency for each phase has been determined and their values are 240 Hz, 228 Hz and 228 Hz for phase A, B and C respectively.
The average value is 232 Hz, with an accuracy of ±2 Hz due to the accuracy of the acquisition system and especially by the on-site dividers and measuring channels in the substations. The resonance frequency is higher for phase A because the distance between phase A and the ground is more important than for the other phases.
As it may be difficult to know the exact values of X''_d and $C_{\varphi/t}$ (§2.2) leading to those frequencies, as several combination of both values may lead to the right frequency, a scan of those parameters taking into account their frequency range has been adopted, which includes the frequency measured on site.
Finally, several palliatives solutions, are described in the following paragraph.

VII. DESCRIPTION AND SIZING OF PALLIATIVE SOLUTIONS

The palliative solutions described in this paragraph, are used, either to shift the resonant frequency of the upstream network to a value leading to lower stresses on the transformers, or implying, if based on resistances, on the dissipation of the energy of the phenomena developed; another solution, acting on the development of the phenomena, is also discussed.

Those palliatives solutions, sized with the EMTP and installed on site in some cases, are the following:

-a) Additional equipment, like the existing lines, which may shift the resonant frequency of the network, away from an harmonic frequency.

To illustrate this point, the influence of a 400 kV line having a length of 140 km and located near the source plant is given below:

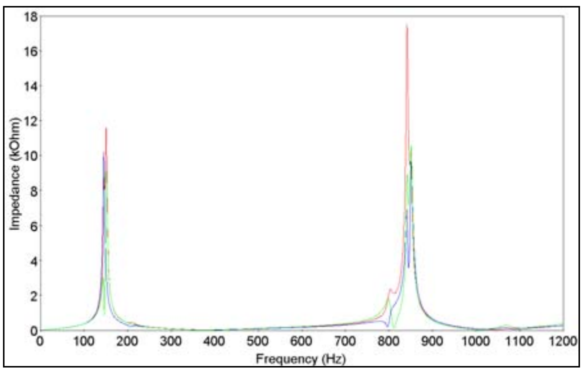

Figure 6 : Direct impedance of the up-steam network, when an additional line is added to the original configuration.

This leads to a total cumulated length of 320 km, which shifts the upstream frequency from 200 Hz down to 150 Hz, with a decrease of the impedance by 40%, from 20 kΩ to 12 kΩ.

This solution is relatively cheap as it may impact the existing network, and its control.

-b) Shunt reactance for the shifting of the frequency of the network; in the case of the French network, a reactance of 100 MVA has been installed in a 400 kV substation, and the solution validated by on site tests, leading to low overvoltages at the transformer entrance. This solution is costly, but may be used especially when the other solutions are difficult to use.

-c) Zinc oxide arresters with a low rated voltage, which may absorb the energy of the phenomenon, and disconnected from the network when the maximum energy capability is reached.
However, their dissipative capabilities are limited, and may not be sufficient in the case of overvoltages of high amplitude, despite a moderated cost.
It can be seen on this figure, where the overvoltage vanishes (see figure 7) but reappears after 1,5 second, when the energy capabilities of the surge arresters are reached:

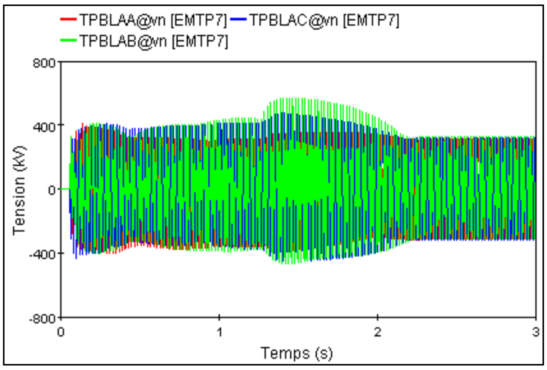

Figure **7** : Temporary harmonic overvoltages with low rated voltage arresters being disconnected at t=1.3 s

-d) Circuit-breakers with pre-insertion resistors (see figure 7 below) , having a resistor value near 1 kΩ , in order to absorb the energy to the phenomenon, that value being different from those used to reduce the switching overvoltages (around 300 Ω, the surge impedance of the network).

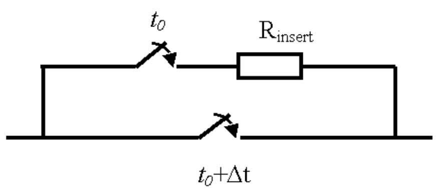

Figure 8 : Circuit-breaker with a pre-insertion resistor.

Typical insertion time of 12 ms have been considered, which is the maximum value reached by the manufacturers, for practical considerations in the circuit-breaker.
With the use of a pre-insertion resistor, the inrush current is reduced, the maximum passing from 1 kA to 400 A, and consequently the losses in the network and also the

overvoltages. It can be seen on the following figures, with and without a pre-insertion resistor :

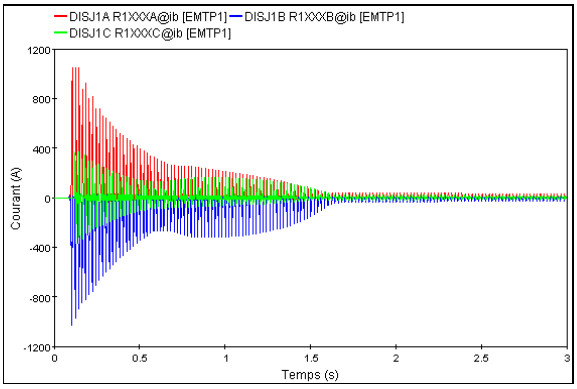

Figure 9 : Inrush current without palliative device

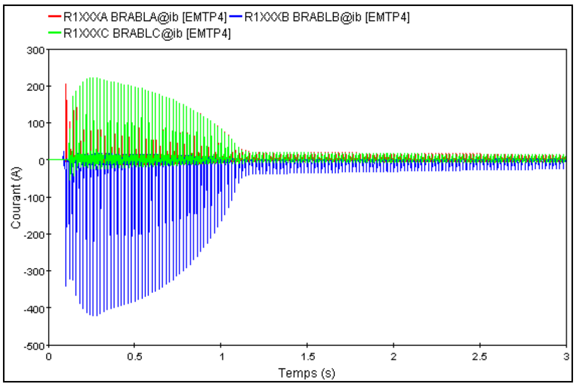

Figure 10 : Inrush current with a pre-insertion resistor of 1 kΩ

A combination between this last solution and the first one implying the use of an additional line may be a very good palliative solution in order to damp the overvoltages to acceptable values.

-e) Synchronous controllers, installed in the control part of the circuit-breakers, which may reduce the inrush currents and consequently the overvoltages; they reduce the total flux at the energization, with the closing times of the circuit-breakers derived by the residual fluxes remaining in the transformers before the switching. Their performance depends mainly on the circuit-breaker performance in repeatabilily.

VIII. CONCLUSION

This paper describes a method for the modeling of the electric network between the source and a target transformer, when two transformers are involved; in that case, a correlation between fluxes in both equipment has been described, which implies consequently a reduction of the number of initial conditions considered when energizing the auxiliary transformer via the step-up transformer.

Secondly, as those energizations may lead those severe stresses, different palliative solutions have been considered, including solutions using the Network capabilities like additional lines, and also circuit-breakers with pre-insertion resistors.

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X. BIOGRAPHIES

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