Reference Circuits for the Ivestigation of Power Systems Transients

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ABSTRACT

Reference circuits, serving for the simplification of complex networks and based on physical analogy can be useful for the preparation and completion of computer studies. The paper presents the fundamental rules of composing reference circuits for distributed parameter lines between two discontinuity points and extends the application of the method over complex networks. Methods are suggested to create reference circuits for multiconductor lines. The application of the method is illustrated by examples.

INTRODUCTION

Power systems involve both lumped and distributed elements. This peculiarity makes power systems transients complex and renders difficult to predict the character of the process, to select the operations and system configurations to be investigated in detail by computers. Power systems transients develop as results of successive reflections at the discontinuity points of the distributed parameter lines. TNA and computer are the tools for the simulation and analysis of these processes. However, beside in addition to the knowledge about the ways of computing it is recommendable to understand the physics of power systems transients in order to check the results and trends gained by computers and to select the parameter intervalls, for which a detailed calculation will be necessary. The experience shows, that reference circuits based on physical analogy, can significantly help in teaching power systems transients and in the practice of electrical engineers.

The accuracy of the results is much higher at computer simulation generally. High accuracy can be also reached by means of sophisticated reference circuits. However the complexity of such circuits reduces the simplicity of the simulation, which is the most important advantage of the application of reference circuits. Nevertheless, there are tasks, where a simple system configuration or the lower demand for the accuracy allow to realise the whole simulation by reference circuits only.

REFERENCE CIRCUITS FOR SINGLE CONDUCTOR-EARTH SYSTEM

Simulation of a line connected to inifinite long lines or resistors (Fig.1).

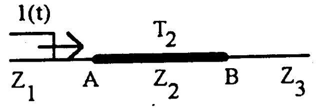


Fig.1.

When a rectangular wave enters a transmission line of finite length (with T_2 wave propagation time), the voltage in points *A* and *B* will be

$$U_{A,k}=\frac{2a}{a+b}\left(1-\frac{1-b}{1+a}\cdot D^k\right)\dots(1)$$

$$U_{B,n}=\frac{2a}{a+b}\left(1-D^n\right)\dots.(2)$$

where

k - the serial number of the actual reflection in point *A*
n - the same in point *B*
D - the product of the reflection coefficients in points *A* and *B*,

$$a=\frac{Z_2}{Z_1}\ ,\quad b=\frac{Z_2}{Z_3}$$

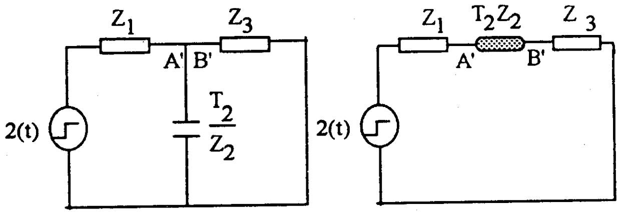
If the sign of *D* is positive, the line of finite length can be represented in the reference circuit by its capacitance

$$C_2=\frac{T_2}{Z_2}\ \text{(in case of } a<1 \text{ and } b<1\text{)}$$

or by its inductance

$$L_2=Z_2\cdot T_2\ \text{(in case of } a>1 \text{ and } b>1\text{).}$$

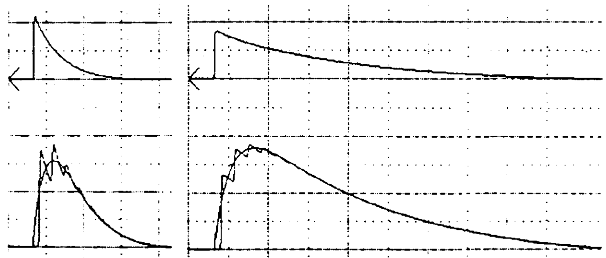
It can be shown, that the error of the simulation by reference circuit will decrease, when the absolute value of *D* increases. The reference circuits for the network in Fig.1 are given in Fig.2a and 2b.



a. b.

Fig. 2

Changing from the rectangular wave over another wave shape is possible using Duhamel's theorem. It can be proven, that the accuracy of the reference circuit will increase, if the change in the value of the function describing the incoming wave shape during T_2 decreases. This trend is illustrated in Fig. 3, where the voltage curves arising in point B of Fig.1 and in point B' of Fig 2.a are shown if Fig. 3 for two different incoming wave shapes. As Figure 3 reflects, the relation of the stepped curve produced by the real network and the curve given by the reference circuit is characterized by the tendency, that the sum of the positive and negative areas between the mentioned curves taken for a time interval of $2T_2$ approach zero.



upper curves: incoming wave
lower curves: voltage in points B and B'
Fig. 3

If the sign of D in equations *(1)* and *(2)* is negative, the voltage in point A and B will be of oscillating character. A series resonance circuit gives references in this case, the capacitance of which is connected to the high impedance side (see Fig. 4)

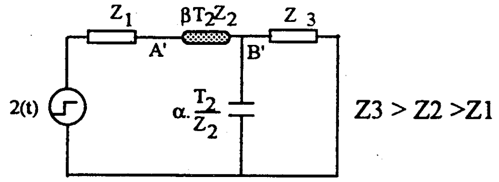


Fig. 4

The values of the capacitance and inductance (i.e. α and β) are to be selected in dependence of the requirements of the simulation. With

$$\alpha=\frac{2}{\pi}\sqrt{a.b}\ \ ...(3)\quad \text{and}\quad \beta=\frac{2}{\pi}\frac{1}{\sqrt{a.b}}\ \ ...(4)$$

the frequency of the oscillation produced by the reference circuit is very close to that of the network to be simulated and the accuracy of the simulation is suitable for waves coming from both directions.

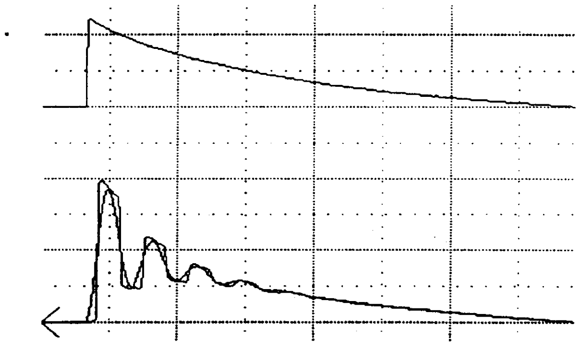
If $a=\infty$ or $b=0$, the equations *(3)* and *(4)* may not be used. For these special cases:

$$a=\infty \rightarrow \alpha=0{,}5 \quad \beta=0{,}81$$
$$b=0 \rightarrow \alpha=0{,}81 \quad \beta=0{,}5\,.$$

The accuracy of the simulation is illustrated in Fig.5, where the shape of the incoming wave and the voltages in point B (see Fig. 1) and B' (Fig. 4) are shown for a=8 and b=0,1.

From the rules described above follows, that the transient behaviour of a line (between two discontinuity points) is determined by its relation to the surrounding network, i.e. by the sign of the reflection coefficients at its ends. So a cable between a low impedance supply system and a faulty network is of inductive character, but it behaves as a resonance circuit after fault clearing and as a condenser, when it is connected to overhead lines on both ends.

The participation of a line of capacitive character in the transient barely changes, when varying the propagation time and surge impedance simultaneously, keeping the ratio C=T/Z invariant.



upper curve: incoming wave
lower curves: voltage in points B and B'
Fig. 5

The same effect occurs in case of an inductive line, when varying its propagation time and the surge impedance simultaneously, keeping L = TZ invariant.

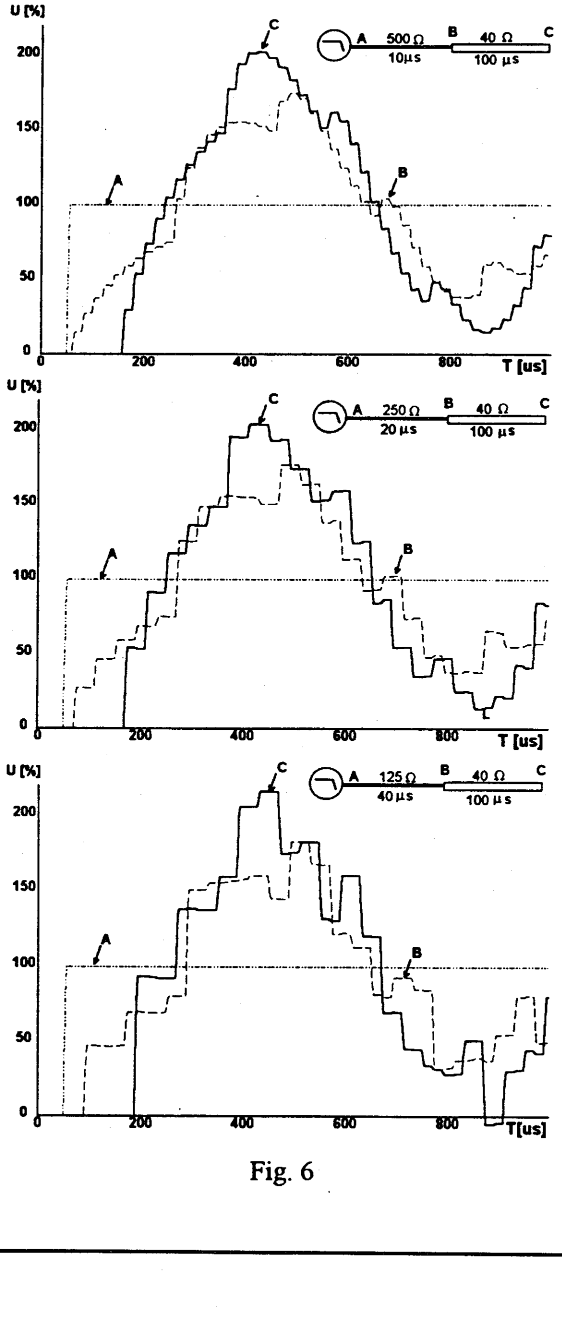


Fig. 6

This statement is illustrated by the voltage curves shown in Fig.6, where the surge impedance and propagation time of an overhead line of inductive character are changed simultaneously. The difference in the amplitude and frequency is very small in the configuration investigated.

Simulation of a line connected to another line of finite length (Fig.7).

If the line to be simplified in the reference circuit is connected to another line of finite length (Fig. 7), the accuracy of the reference circuit will decrease to a certain extent.

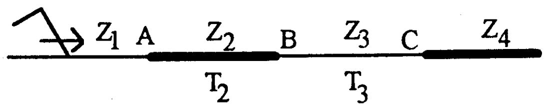


Fig. 7

If $\frac{T_3}{T_2} \geq 1$, the line with parameters Z_2 and T_2 is to be simulated as in case of $T_3 = \infty$. If $\frac{T_3}{T_2} \langle 1$, one has to take into account the effect of the wave reflection in point *C* as well. It can be done by creating a fictitious reflection coefficient $\rho_{42} = \frac{Z_4 - Z_2}{Z_4 + Z_2}$. The simulation of line *AB* in the reference network has to be based on a compromise: it has to satisfy also to the reflection coefficient ρ_{42}.

Table 1 helps to select the suitable simulation. In the table ρ_{21} and ρ_{23} mean the reflection factors in points A and B respectively.

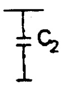
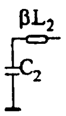
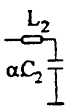
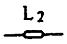
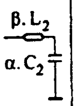
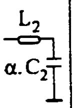
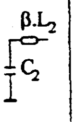
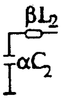
$\rho_{21} \cdot \rho_{23} > 0$				$\rho_{21} \cdot \rho_{23} < 0$			
$\rho_{23} > 0$		$\rho_{23} < 0$		$\rho_{23} > 0$		$\rho_{23} < 0$	
$\rho_{42} > 0$	$\rho_{42} < 0$	$\rho_{42} > 0$	$\rho_{42} < 0$	$\rho_{42} > 0$	$\rho_{42} < 0$	$\rho_{42} > 0$	$\rho_{42} < 0$
	 $\beta = 0{,}4$	 $\alpha = 0{,}4$		 $a = \frac{Z_2}{Z_1}$ $b = \frac{Z_2}{Z_4}$	 $\alpha = 0{,}4$	 $\beta = 0{,}4$	 $a = \frac{Z_2}{Z_1}$ $b = \frac{Z_2}{Z_4}$

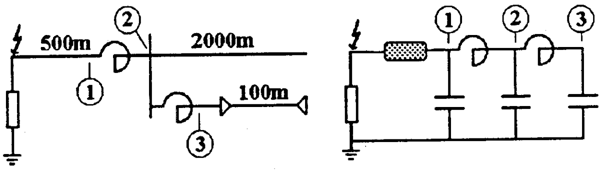
Table 1

In the configurations, determined by the 5th and 8th columns α and β have to be computed according to the equations *(3)* and *(4)* using the values of *a* and *b* given in the mentioned column of the table.

REFERENCE CIRCUIT FOR COMPLEX (LUMPED & DISTRIBUTED) NETWORKS

The rules of simulation by means of lumped elements can be used advantageously also when applying the method of Bewley or Bergeron, if the network contains lumped capacitor or inductance. In this case the capacitor or inductor has to be substituted by a short (compared with the propagation time of the neighbouring distributed elements) line, using formulae $C = \frac{T}{Z}$ and $L = ZT$, keeping C or L invariant. So the number of the discontinuity points increases, but the network becomes to be able for handling by the mentioned methods.

Applying the rules summarized in Table 1 successively, reference networks also for relatively complex system configurations can be created. An example is given in Fig. 8 wich illustrates the effect of a lightning stroke in a multiline substation. The curves show a good agreement of the stresses in points 1, 2, 3 of the real network and in the corresponding points of the reference network. The reference network and the curves of Fig.8 reflect, that a lightning stroke can cause an oscillating transient in the substation. The oscillation frequency depends on the distance between the faulty point and the substation, on the inductance of the reactors, on the capacitance of the cable and of the unloaded overhead line. It is remarkable, that this frequency lies usually in the range of the self frequency of the transformer and so resonance overvoltages can arise inside the transformer, even if it is protected by arresters at its terminals.



network configuration reference network

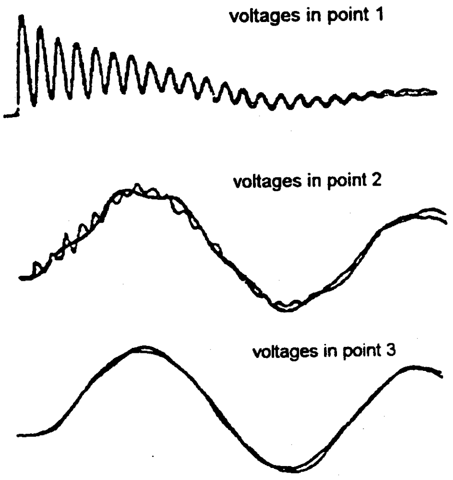
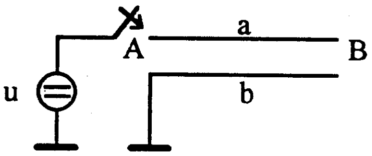


Fig. 8

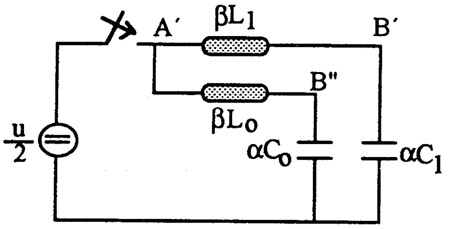
REFERENCE CIRCUITS FOR NETWORKS CONTAINING MULTICONDUCTOR LINES

There are transients in multiconductor systems, during which waves propagate in one mode only (e.g. three - phase back-flash, simultaneous energization of a transmission line with symmetrical load). The rules serving for the composition of the reference circuit are the same as for single conductor - earth system. The character of the reference circuit (capacitive, inductive, oscillating) are determined by the relation of the surge impedance of the line in the existing mode to the modal impedances of the surrounding network elements. The parameters of the reference circuit are to be computed on the basis of the modal surge impedance and propagation time of the line.

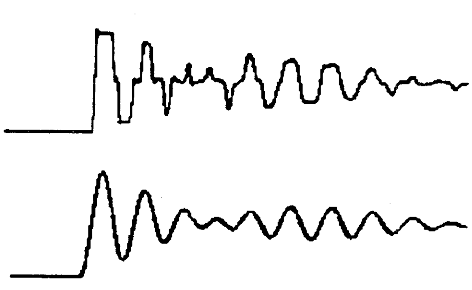
If the operation initiating the transient phenomenon excites wave propagation in both modes and the discontinuity points are symmetrical (the sign and the value of the reflection coefficients are equal in each phase), two modal transients will take place separately. Consequently, individual reference circuits have to be composed for the line mode and ground mode. Fig. 9 shows an energisation transient in a two - conductor - earth system with symmetrical discontinuity points and the modal reference circuits. The figure illustrates the phase voltages at the open end of the line (point B) and the corresponding voltage curves given by the modal reference circuits.



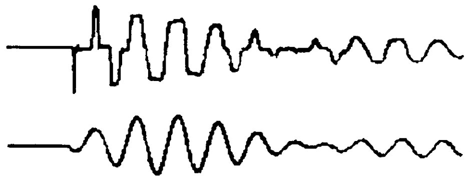
network configuration



modal reference circuit



Voltage in phase *a* (point B)
upper curve: real network
lower curve: reference network



Voltage in phase *b* (point B)
upper curve: real network
lower curve: reference network
Fig. 9

The reference circuit gives the open end voltage in phase *a* as $U_{B'}+U_{B''}$ and $U_{B'}-U_{B''}$ in phase b. This circumstance explains the beating character of the phase voltages.

The accuracy of the reference circuit seems to be very low in phase *b* immediately after starting the process. This is caused by the short peak occurring in the real network voltage, being a consequence of the difference between the line mode and ground mode propagation times. As it was mentioned before, the accuracy of the reference circuit decreases at sudden changes in the wave shape. Decreasing the accuracy can be explained by the areas between the curves of the real network and reference circuit.

Considering two identical resonant circuits, both of them will produce the same self frequency f during a transient. However, if they are coupled, two different frequencies will occur:

$$f_x=\frac{f}{\sqrt{1-K}} \text{ and } f_y=\frac{f}{\sqrt{1+K}}$$

where K is the coupling factor. The frequency of the energisation transient of a single conductor line is $f_s=\frac{1}{4T}$. According to the reference network shown in Fig. 9 the frequencies occurring during the same transient, when there is a two phase line of the same length are: $f_1=\frac{1}{4T_1}$ and $f_0=\frac{1}{4T_0}$. If the value of coupling between the abovementioned resonant circuits agrees with that between the conductors of the two - phase line, then

$$f_x\!:\!f\!:\!f_y=f_1\!:\!f_s\!:\!f_0$$

So the line mode and ground mode velocities can be derived from the oscillation of two coupled conductors with the same length.

If multimodal waves arise at the point of the operation initiating the transient process and the discontinuity points are quasi-symmetrical (only the signs of the reflection coefficients are equal for each phase conductor at the discontinuity point but not the values), the configuration of the reference network will be the same, as shown in Fig. 9. One has to build into the modal reference circuits the arithmetical mean of the loading impedances at the quasi - symmetrical reflection point in this case.

At a number of transients taking place in networks containing unsymmetrical discontinuity points as well, there are conductors, for which the product of the terminal reflection coefficients is positive. In these configurations that (active) phase conductor will determine the character of the phenomenon the terminal reflection coefficients of which are of opposite signs. The other, capacitive or inductive phase conductors influence on the oscillation frequency in the active conductor to a certain extent. Starting from the frequency, characterizing the oscillation of a single conductor, a coupled conductor of inductive character makes the frequency of the active phase to increase, and a coupled conductor of capacitive character to decrease. Consequently, the phenomenon can be simulated by one reference circuit, taking into account the effect on the propagation time of the coupled conductors at the calculation of the reference circuit parameters. A fictitious wave velocity v^* can be re-calculated from the frequency f_r of the reference circuit of a line length l, using the equation

$$v^* = 4 \cdot l \cdot f_r,$$

EXAMPLES FOR THE APPLICATION OF REFERENCE CIRCUITS FOR MULTICONDUCTOR LINES

1.The principle described above has been used in the elaboration of a fault locator of high accuracy which computes the fault distance from the frequency of the fault clearing transient [3]. Analysing the spectrum of this transient, the fault locator establishes the fundamental frequency and calculates the fault distance on the basis of v^*.

2.Reference networks can be used advantageously for the analysis of the behaviour of the secondary arc, the duration of which determines the lower limit of the dead time in the cycle of single phase reclosing. If the line is relatively short, or if it is provided with four legged shunt reactors, then the secondary arc is of intermittent character during the predominant part of its life [4]. Consequently, the transients arising in the interval of intermittent burning are decisive for the secondary arc duration time.

The scheme of the network and the reference circuit for phase a are shown in Fig. 10. The reference circuit involves the effect of the healthy phases, since its parameters have been computed considering the velocity v^*. By opening and closing the switch S one can simulate the extinction and reignition of the intermittent secondary arc.

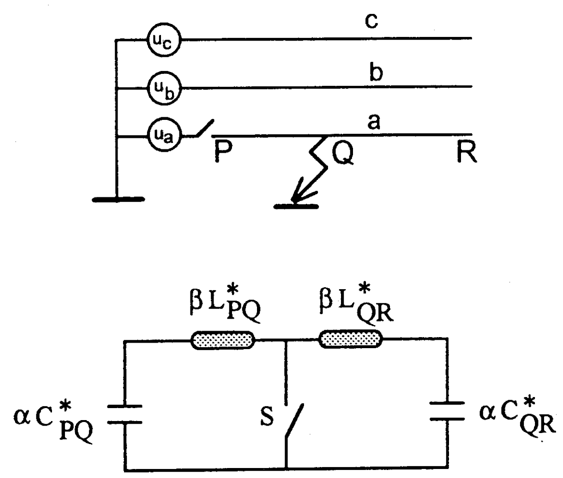


Fig. 10

From the reference network follows, that every reignition initiates an oscillating transient in both resonance circuits. It can be shown mathematically, that the time difference between the moment of the reignition and the first current zero in the arc is independent on the place of the fault and its value is equal to 2T*, excepting the case, if the fault is in the middle of the line, where the time difference is T*. The intermittent secondary arc usually extinguishes temporarily at the first current zero . Therefore each reignition causes a current impulse of duration 2T*. Field experiments support this conclusion.

The effect of a reignition current impulse on the thermal condition of the arc plasma depends on the duration of the impulse among others. The length of the line influences on the secondary arc life time in this way during its intermittent stage.

A further conclusion coming from the reference circuit of Fig. 10 is, that the transient initiated by a temporary extinction contains a component of frequency

$f = \frac{1}{2T^*}$, which is independent on the place of the fault. Connecting filters tuned on this characteristic frequency to the line terminals, the moment of the final extinction of the secondary arc can be established. Such a reliable information can be used for improving the successfulness of reclosing or can serve as a basis for an adaptive reclosing.

3. The process of the energisation or re - energisation of a three phase line is influenced by the sequence of the phases in the operation and on the time delay between

switching on the individual phase conductors. A reference network can be composed , which explains the role of the parameters during this complex transient [5].

Switching on transient of the first phase can be studied by a single reference circuit, the parameters of which are computed taking into account the other, passive phases. So the frequency in this stage will determined by v^*, which is near to f_s. When switching on the second phase, a second resonance circuit gets active, the self frequency of which will be the same, as at the first phase switching on. The third switching on operation initiate a futher transient component, in the frequency of which the line mode and ground mode frequencies occur. Fig.11 shows the whole transient phenomenon reflecting the interaction of the resonance circuits of different frequencies.

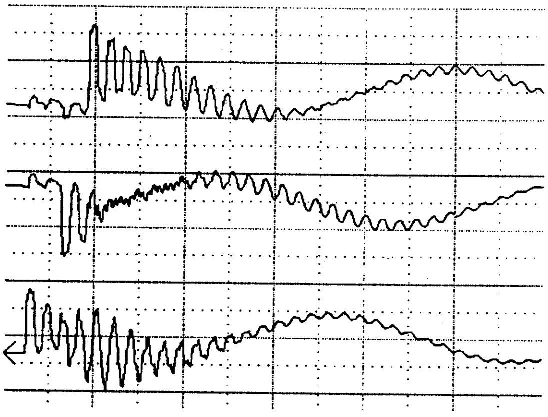


Fig. 11

CONCLUSIONS

1. Reference networks containing lumped elements only, can be composed for real single phase system configurations, participating in the power systems transients. The accuracy offered by the reference network depends on the complexity of the system to be simulated and on the kind of the excitation (wave shape, etc.).

2. There are possibilities for the simulation of multimodal transients by relatively simple reference circuits. The accuracy of the simulation will be lower to a certain extent, than in a single phase network, but these reference circuits also reflect the character of the transients.

3. The application of reference circuits helps in understanding the physics of power systems transients, since here the successive wave reflections will be replaced by simple processes, taking place in lumped circuits. Reference circuits facilitate to predict the character of transient, to estimate the influence of the individual parameters on the process and helps in checking the results of detailed computing.

4. The transient processes, taking place in lumped reference circuits can be decribed by mathematical equations as a rule. This circumstance helps in the generalization of the results obtained by computer simulation.

5. Reference circuits can be used for the simulation of the supply system or the loads, at which a high accuracy is not required usually.

ACKNOWLEDMENTS

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