SYNCHRONIZATION OF PCM NETWORKS*

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Introduction

It was A. H. Reeves who had the pulse code modulation (PCM) technique patented in 1938 when working with the I.T.T. Laboratory in Paris. In lack of appropriate technical conditions (first of all, of fast-operating, reliable, yet low-cost two-state active elements), however, its practical application had to put off for about 20 years. Then, with the advent of semiconductors, the PCM transmission technique could be brought into being, and it made rapid strides in the early '60s.

Since then, a large quantity of channels have been produced, and today the number of PCM transmission channels can be estimated at about half a million throughout the world. Such a prosperity (dating back to 8 or 10 years) may account for the nature of PCM techniques. PCM is of versatility for use and simple in realization; the higher the number of its fields of use, the more natural is the increasing demand on, and the possibility of an integration.

The efforts made to achieve such an integration are, however, incarnated not only in the handling of messages as equally ranked, characteristic of a so-called "horizontal integration", but also in the identical method used for their transmission and elaboration, typical of the so-called "vertical integration". This latter is somewhat lagging behind the former at present, because digital switching technique, as one of the most important manipulation methods with message transfer, does not yet produce but initial tentative results.

Even now it can be ascertained that for digital signals the basic methods usual with transmission and switching are not so expensive as they would be in case of analogue signals, and in addition, the methods will have less distorting influence on a digital message. In a PCM network a major part of the costs, and quality distorsions in messages almost entirely, should be imputed to converting analogue signals into digital ones, and v.v. Thus,

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a perspective trend should be such as to develop integrated digital networks, i.e. networks where only a minimum number (ideally not more than one) of such conversions-reconversions is then needed.

For the time being, all the questions pertaining to integrated digital networks are still purely of academic nature.

1. On integrated networks

In technical life it is a natural and expedient endeavour to approximate integration as far as possible. This is to the own interest of the manufacturer, of the operator, and of the user as well. The user's interest is of particular importance whenever a service is concerned. And yet, telecommunication is one of the most important services rich in content of political, cultural, social and economic nature.

The demand on telecommunication services, particularly in the scope of telephony, is steadily increasing all over the world. Actually, these demands cannot be met but by using the most up-to-date policy, this being the only economic one, on the one hand, and due to the performance obtained, on the other.

Mention is usually made of two types of network integration, viz.:

- *integrated digital network*, i.e. a network operating on a time-division basis, and in which any message is transferred in a digital form through each switching centre and along the whole transmission line;
- *integrated services network*, i.e. a network simultaneously handling messages of different services (such as telephony, telegraphy, data-transmission, etc.).

On a multiplex highway (switching centres included) messages which happen to occur simultaneously may be handled in three different ways, i.e. either in the form of space-division, or frequency-division, or of time-division (leaving by the time the possibility of a sequency-division, arising from the Walsh-functions, out of consideration, for practical purposes). Theoretically, each one of these three "divisions" is suited for a multiple exploitation of transmission lines, and to set up the switching, field and the control of a given exchange.

Fig. 1 shows, for a given area, how the network within this area has been, and keeps on being developed. The vertices of "the state-triangle" indicate a 100 per cent space-, frequency- and time-division respectively. If a 90 per cent purity can practically be considered as integration, so it is necessary, as to be able to speak of any one of the three types of network integration that the curves, parametered in years and showing the improvement of transmission techniques and switching techniques, join together one of the small

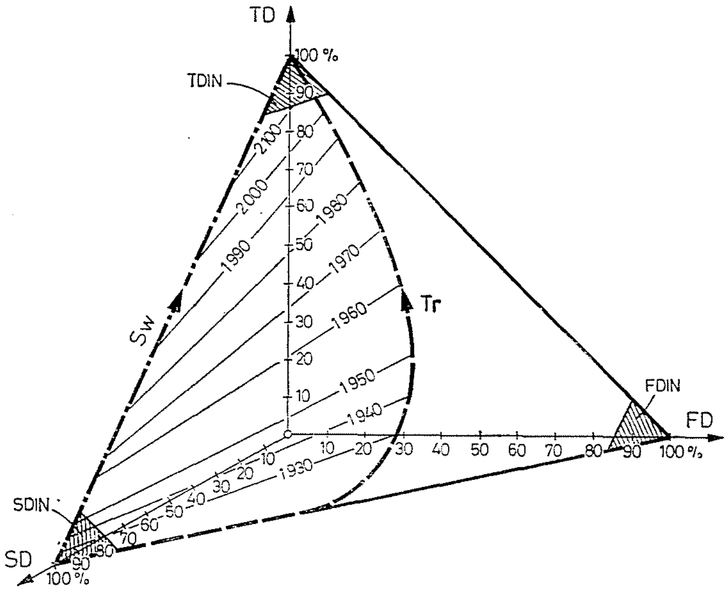


Fig. 1. Time diagram for the general development of networks. (The rough-estimations on the curves indicate the time in years.) SD = Space division; FD = frequency division; TD = time division; IN = "purity" of an integrated network (practically above 90 per cent) Sw = switching techniques; Tr = transmission techniques

triangles close by the vertices of the state-triangle. Now, considering the trend of recent development, the achievement of integrated time-division (digital) networks seems to be very likely. So, of course for a smaller area (as a model network, for example), a time-division network may become real even within a few years, whereas for greater areas, or rather on a higher network level, they can hardly be expected to come into general use before the turn of the millenary.

2. General terms. Conception of a network synchronization

A PCM network is a digital one in which all informations concerned with the transfer of messages and their routing, as well as in setting up and maintaining or releasing (i.e. controlling) connections, always flow in the form of pulse-streams through the nodes (switching centres), and on the transmission lines (either wired or wireless ones) connecting these nodes.

In order to achieve a correct transfer of all the messages, and to ensure an undisturbed control, the pulse-streams have to be "organized"; it is necessary, namely, to be able to recognize, and what is more, unambiguously, the commencements of the 8 kHz-cycles (frames and multiframes) adequate to the sampling theorem so that, referred to them, the positions of the subframes of the multiframes and those of the time-slots of the frames can duly be defined. The process enabling us to do so is termed "framing", which often is referred to as "synchronization".

In fact, "framing" is practically not a synchronization, as

a) it is postulatory for its performance that the frequency of the bits of the pulse-stream to be organized, as well as, in case of a large-scale network, the phases between the bits of the lines leading to the same node, are available beforehand and to the extent desired;

b) "framing" is needed in point-to-point connections, too, though in such cases the phase relationship of the bits is of no importance at all, and even the value of the bit-frequency is relatively unimportant.

Accordingly, the conception of "framing" carries the implication of organizing a frame from the bits of a pulse-stream already synchronized; while the term "synchronization", concerned with large-scale networks, only can (or rather has to) imply the "adjusting together" (harmonizing) the clocks of the nodes so as not to permit the arrival of pulse-streams at the common highways, unless they have carefully specified frequencies and well-defined phases. This is then the kind of timing that can be called "bit-synchronization", or briefly (and with good reason, after all) "synchronization".

3. Synchronization of PCM networks

According to the arrangement of the highways interconnecting its nodes, and with a view to the part to be played in respect of the traffic, a network consisting of several nodes may have various forms of construction, i.e. those of star-shaped, meshed, polygonal, and bus-line construction, as well as the star-shaped one combined with transversal connections.

In practice, the two wide-spread network structures are the star-shaped one with transversal connections, and the meshed form (this latter being generally used in an incomplete way as not every pair of nodes is necessarily interconnected by a highway). Thus, in discussing PCM networks, there are only two ideal networks which should be primarily taken into account, viz. the star-shaped and the meshed ones.

A digital network consists of two parts, i.e. a set of nodes, each node involving a clock (pulse generator), and a set of interconnecting highways conveying the pulse-streams of the code-words made up of pulses produced by the clocks in the nodes. According to the actual interdependence of these clocks, there are three feasible forms of network organization, i.e.:

a) where clocks are independent of one another;

b) where all the clocks are in a master–slave relation to one another;

c) where there is a mutual synchronization among the clocks.

Now, on considering the circumstances, whether there are master clocks in a network or not, and if so, how many such clocks are existing, and again, what is the dependence of the slave clocks on one another, and on the master clocks, respectively, networks can be classified according to these restraints upon synchronization; the result obtained is shown in Fig. 2.

Further on let us consider, one by one, the network synchronization methods displayed in Fig. 2.

3.1 *Plesiochronous network*

A network in which the clocks are independent of one another shows performances as follows:

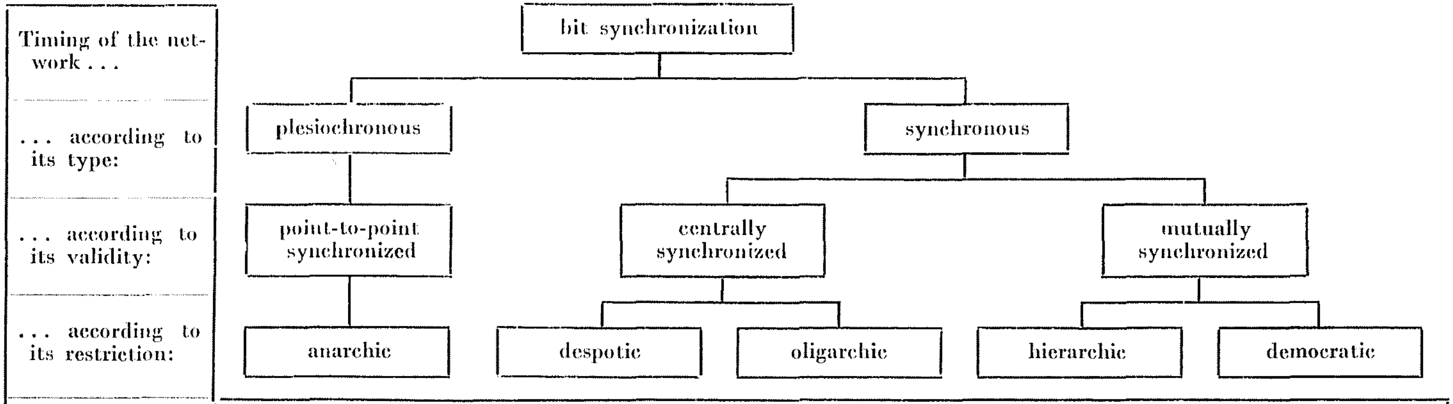
a) all the clocks are wanted to be of high accuracy and able to keep their nominal frequency with a precision of 1 part in $10^9 \ldots 10^{10}$;

b) it consists of a set of point-to-point synchronized interconnections, that is to say, as far as synchronization is concerned, these highway interconnections are independent of one another.

Such a network makes us, however, to face one of the most delicate questions, viz. how to substitute for a clock, if it becomes faulty. The fact that clocks, normally assumed to be independent of one another, have to substitute, even if only in a manner of reduced value, for a faulty clock, will lead to inconsistency and, consequently, to dissimilar results. Such a requirement is conditioned upon an intercommunication among the clocks even if faultless, since, if the clocks are wanted to assist one another in their functions, the occurrence of a fault will have to be noticed which needs continuous watching. Thus, independent clocks are, in their true aspects, depending on one another.

3.2 *Synchronous network*

The fundamental principle of organizing a synchronous network is the master–slave relation existing between a main clock and an auxiliary clock. One master clock (main clock) may control several slave clocks (auxiliary ones) resulting, in this way, in a network of star-shaped construction. The clock with the utmost accuracy has to be placed in the centre of the star. Upon this master clock there are high demands to be made concerning its frequency stability and reliability. Practically, there are no really ideal star-shaped networks and the transverse circuits do not fit in the general hierarchy of the network; one of their ends, their initial point will, though, synchronize the section subordinate to this end, but the final point cannot be synchronized by the initial one as the former must be synchronized by the node superior to it in the hierarchy. Here the chain of synchronization must, consequently, be broken so as not to get the system over-defined.



. . . according to its restriction:	anarchic	despotic	oligarchic	hierarchic	democratic
Dependence among clocks:	independent clocks of the same order	a single master clock, the other clocks are controlled by it, and are independent of each other	several master clocks, the other clocks are controlled by them, and are independent of each other	several master clocks, the other clocks are controlled by them, and mutually by each other	clocks of the same order, controlled mutually by each other
Accuracy of the clocks (order of magnitude):	10^{-10}	$10^{-9} \ldots 10^{-10}$ and 10^{-7}, respectively	$10^{-9} \ldots 10^{-10}$ and 10^{-7}, respectively	$10^{-9} \ldots 10^{-10}$ and 10^{-7}, respectively	cca. 10^{-7}
Availability (MTBF):	40 years	40 and 10 years, resp.	40 and 10 years, resp.	40 and 10 years, resp.	cca. 10 years

Fig. 2. Build-up of the network synchronization

3.3 *A mutually synchronized system*

If none of the clocks in a network can be looked upon as a distinguished one as far as control is concerned, the network is called a democratically synchronized one. Stability is the most important parameter of a mutually synchronized network, and this means that, prior to occurrence of any failure, the network has to present an equilibrium condition, and as soon as a fault occurs the network gets into a new equilibrium condition which may differ from the former one, an impossibility if stability is missing.

From the movements and work carried out by Study Group Special D. of the C.C.I.T.T. (International Telegraph and Telephone Consultative Committee — one of the international institutions of the ITU) it is very likely that future integrated digital networks will all be based on mutual synchronization.

One of the greatest disadvantages shown by such networks is the fact that it is very difficult to describe their behaviour, stability and other performances by exact mathematical methods.

The author took notice of similar stability problems encountered in co-operating energy systems which, too, are multi-node networks. Generators in these nodes synchronize one another and, in this way, they will get into an average steady state. If a sudden break-down of one of these generators upsets the balanced condition of the network, this latter will, as soon as a transient phenomenon has set in, take on a new equilibrium condition. Is such a transient phenomenon too "hot", the network becomes then "swinging" what may result in catastrophic failures.

There is such a striking parallelism between these two kinds of networks that, hereinafter, we shall attempt to adapt to integrated digital networks the results obtained for co-operating energy networks. We have good reason for doing so, as the topic of energy systems is much the best elaborated (and computerized), due to the fact that such power networks had already been investigated for a long time, before integrated digital networks started to be studied.

4. Parameters of a mutually synchronized network

4.1 *Linear control system*

Let an integrated digital network consist of N nodes, all being geographically separate ones, and interconnected by direct transmission paths. Each node (station) has its own local clock (oscillator). A control signal may cause the self-frequency of every local clock to vary proportionally. In the absence of any particular control, each of these clocks will operate on its natural-frequency. Though these latter frequencies are nominally all equal they may, however, be practically different from one another within a certain tolerance limit. The transmission paths (by which any two of the stations will, either directly, or — through an other station — indirectly, be connected) always cause a definite transmission delay.

In a linear control system, each station receives the phases coming from any neighbouring station and takes their averages which, then, will be compared with the local phases; the error signal is used for controlling the local oscillators. Such a system has been found by V. E. BENEŠ to be a steadily stable one.

4.2 *Mathematical model of a connected network with N nodes*

Let the number of nodes in the network be $N \geq 2$. Each node has its local clock operating at a natural frequency f_i. The actual frequency of the i^{th} oscillator (which may differ from f_i within given limits) can simply be regarded as a phase variation measure $p'_i(t)$.

Now, let τ_{ij} denote the delay of a transmission from the j^{th} node to the i^{th} one. Consequently, it is possible to measure the phase difference $p_j(t - \tau_{ij}) - p_i(t)$ between the signal received at the j^{th} node, and that of the local clock. Signal phases entering a node are then averaged (weighted) by a non-negative weighting factor a_{ij}, where $\sum_{j=1}^{N} a_{ij} = 1$. The observed mean phase, produced in this way, can now be multiplied by a non-negative factor λ_i (of dimension s^{-1}) so as to get the frequency deviation of the local clock in question.

If $r_i(t)$ denotes the control signal applied to the i^{th} oscillator at a given time t, the instantaneous frequency will be:

$$p'_i(t) = f_i + r_i(t)\,, \tag{1}$$

where $i = 1, 2, \ldots, N$.

In so far as the model is of linear control, the control signal will be proportional to the phase shift. Proportionality factors are: a_{ij} and λ_i. The phase positions of the neighbouring nodes must, however, also be taken into account, and thus:

$$r_i(t) = \lambda_i \cdot \sum_{j=1}^{N} a_{ij}[p_j(t - \tau_{ij}) - p_i(t)] \tag{2}$$

where $i = 1, 2, \ldots, N$. Making use of (1), Eq. (2) will take the form:

$$p'_i(t) = f_i + \lambda_i \cdot \sum_{j=1}^{N} a_{ij}[p_j(t - \tau_{ij}) - p_i(t)] \tag{3}$$

where, again, $i = 1, 2, \ldots, N$.

Realizing λ_i by means of a filter having a transfer function $H(s)$, where $\int\limits_0^\infty h_i(t)dt = \lambda_i$ and $i = 1, 2, \ldots, N$, Eq. (3) will take the form:

$$p_i(t) = f_i + h_i * \sum_{j=1}^{N} a_{ij}[p_j(t - \tau_{ij}) - p_i(t)] \tag{4}$$

where $i = 1, 2, \ldots, N$. Relationships of the type (4) are called systems equations.

These factors a_{ij} constitute an $N \times N$ matrix capable of rendering any topological information relating to the structure of a network.

4.3 *Start of a synchronized operation*

The time axis is chosen so that the synchronized operation starts at time $t = 0$ (a control voltage will be connected to the oscillators). The oscillators are assumed to have run in the time range $t < 0$ with their natural frequencies, and even for a period of time long enough to permit each node, in spite of any transmission delay, to receive the signals of the other nodes. If the control switches close at $t = 0$, this will usually cause an immediate change of frequency at each node. Practically it is of primary importance to be able to predict the frequencies to which the oscillators of the individual nodes will finally adjust themselves. The consideration below deals with this problem.

4.4 *The linear model*

The Laplace transform of the systems equations (4) can be written as:

$$sP_i = H_i \sum_{j=1}^{N} \hat{a}_{ij} P_j - H_i \cdot P_i + \frac{1}{s} f_i + p_i(0) + Q_i(s) \tag{5}$$

where

$$\hat{a}_{ij} = a_{ij} \cdot \exp(-s\tau_{ij}), \quad \text{and}$$

$$Q_i(s) = H_i(s) \sum_{j=1}^{N} a_{ij} \int\limits_{-\tau_{ij}}^{0} p_j(t) e^{-st}\, dt,$$

while $P_i(s)$ is the Laplace transform of $p_i(t)$. On the transmission paths, $Q_i(s)$ is, at time $t = 0$, the contribution by "content" to the i^{th} oscillator frequency for times $t > 0$. Transform systems equations (5) can, in principle, be solved for phases $p_i(t)$ whenever $t \geq 0$.

In the present paper we have set out from systems equations showing the forms as follows:

$$P_i = \frac{1}{s + H_i(s)} V_i + \beta_i(s) \sum_{j=1}^{N} a_{ij} P_j, \tag{6}$$

$i = 1, 2, \ldots, N$
where

$$\beta_i(s) = \frac{H_i(s)}{s + H_i(s)},$$

$$V_i(s) = \frac{1}{s} f_i + p_i(0) + Q_i(s)$$

and β is the transfer function of feed-back. According to paragraph 4.5, stability is achieved whenever the condition $\beta < 1$ is satisfied.

4.5 *Steady-state frequency and the stability*

Assume the (physically quite natural) conditions

$$|\beta_i(s)| < 1, \quad s = j\omega, \quad \text{and} \quad \omega \neq 0 \tag{7}$$

to be satisfied. Eventually, the stationary state frequency of the i^{th} oscillator is determined by the relationship

$$f = \sum_{j=1}^{N} \gamma_j f_j \tag{8}$$

where γ is dependent on the matrix of the weighting factors and on the (constant) transmission delay τ_{ij}, as well. Evidently f is independent of i, and that the system is seen to be stationarily stable as the frequencies from all the oscillators tend to a common frequency.

4.6 *Nature of the steady-state frequency*

The evidence that the common frequency in Eq. (8) may be even lower than the lowest one from among the frequencies of the oscillators belonging to the system is an interesting physical fact. The reason for this is that the frequency control of the *individual* nodes is a straightforward function of the *overall* phase differences. The interposition of such delays will result in phase slips "lowering" in this way the frequencies of the individual stations.

4.7 *Transient stability of the linear model*

From the above-mentioned issues it can only be concluded on transient stability that a parameter change proceeding "slowly" in time will result in a similarly "slow" frequency change.

4.8 *Effect and computation of transient phenomena*

The question arises what will happen if in one or more of the oscillators or transmission paths a catastrophic failure occurs. An event like this is taken for such a transient phenomenon as tending — in general — to the well-defined stationary state through such "overshoots", however, as may cause the system, by chance, due to its overload, to get disintegrated even before reaching the stationary state, resulting, in this way, in a complete breakdown of a part, or even the whole of the network. This problem, for all we know, has not been cleared up yet in the literature.

Consequently, we should make use, as a possible solution, of the results available, for the time being, in the field of the co-operating power networks.

5. Transient stability of co-operating power networks

5.1 *On the co-operating power networks*

Co-operating power networks are made up of power stations interconnected by high-tension transmission lines, and of groups of big consumers. The construction of such a network may be either of radial, or of mesh-connected or of bus-connected type which, in integrated digital networks, correspond to star-shaped, meshed, or bus-connected systems, respectively.

Heavy-duty generators at the nodes are pretty well all synchronous machines. In stationary conditions all these synchronous machines, operating in the nodes of the network, are in synchronism with one another. Consequently, as far as conditions of a stable operation are concerned, two questions may arise, i.e.

- what conditions are required for the stability of a stationary operation;
- what is the condition of a transient stability.

Impulsive load variations will cause the angle-position phase of the rotors to change. Inertia mass of the rotors, on the one hand, and the magnetic field (as a "resilient" medium), on the other, constitute a two-store system capable of swinging. Because of such a swinging a machine may fall out of synchronism what will also act upon the machines at the other nodes of the network.

5.2 *Transient stability*

The investigation has been based on the equation of motion expressing the equilibrium between mechanical and electrical forces, i.e.

$$\theta \frac{d^2\delta}{dt^2} + K \frac{d\delta}{dt} = M_m - M_v , \tag{9}$$

where θ denotes the common moment of inertia of the rotors of both the generator and the turbine, δ indicates the phase position of the rotor, K represents an attenuation factor (frictional loss, etc.), that with a fairly good approximation, can be taken for zero, while M_m and M_v are the mechanical and electrical moments, respectively.

5.2.1. *Examination of the transient stability by means of a digital computer and a network model*

Equations of motion may not always be solved in an exact manner, if not by a digital computer. In lack of a computer, they can be solved by the wide-spread method of finite differences. It is, however, inconvenient on a computer, as the perpetual transfer of function values and differences, required by index variation in the storage unit (memory), would considerably slow down the run of a program, besides of requiring a large storage capacity.

For a computer-aided design the Runge—Kutta—Gill method is a very suitable one and it has a bearing upon the step-by-step integration method.

The phase-position of rotating machines is described by a differential equation, transformed from (9):

$$T_i\delta_i'' + \sum_{j=1}^{N} K_{dij}\delta_{ij}' = P_{mi} + P_{vi} \tag{10}$$

where $i = 1, 2, \ldots, N$, however $i \neq j$, while T is the spin-round obtainable from the moment of inertia, and K_d is a matrix implying the topological distribution of the attenuation (friction) factors.

This problem was solved by a computer at the VILLENKI (Budapest) in 1963 for a system of max. 20 nodes. Since then, also solutions for systems of up to 143 nodes have been reached.

6. Application of the calculation of transient stability in co-operating power networks for synchronizing integrated digital networks

6.1 *Physical and mathematical bases for analogy*

Both networks generally consist of several nodes mutually synchronizing one another. Both networks have a control system highly responsible to transient phenomena.

The frequency and its variation are described for either of these networks by systems of differential equations where the structure of the network is represented by a matrix, dependent on the topology of the actual network.

The two sets of differential equations are, however, not quite identical due to the simple fact that in one of these sets the stability parameter is the line transmission delay, while in the other set, this parameter is the inertia of the rotors.

For an integrated digital network the primal system of equations is given in (3), while that for a co-operating power system in (10). These latter equations are of the construction below:

$$a\delta_i'' + \sum_j b\delta_{ij}' + c\delta_{ij} = d \tag{11}$$

where δ_i is the angle-position of the i^{th} node, $\delta_{ij} = \delta_i - \delta_j$, while a, b, c and d are constants. The construction of Eq. (3) is as follows:

$$ap_i' + \sum_j bp_{ij} = c \tag{12}$$

where p_i is the angle-position in node i, $p_{ij} = p_j(t - \tau_{ij}) - p_i(t)$, while a, b, and c are constants. Eqs (11) and (12) are of similar construction. Parameter δ is an angle-position, yet not an absolute one but a relative one, referred to the angular velocity ω_0; thus, a next higher-order differentiation of parameter δ, with respect to the phase-position p, will not be inconsistent with the analogy of the two systems of equations. Quite the contrary, it even seems to support this analogy.

6.2 *Confrontation of the two networks*

It follows from the foregoing paragraph that it is possible to draw a comparison between the two networks. The most important parameters, occurring in both of the networks and revealing analogy, have been tabulated in Table 1.

Table 1

Confrontation of parameters

Parameters showing analogy			
Co-operating power networks		Integrated digital networks	
Symbol	Name	Symbol	Name
f	frequency	f	frequency
ω	cycle	ω	cycle
δ	angle-position	p	phase
K_d	attenuation matrix	A	weighting matrix
n	number of power sts	N	number of nodes
P_v	$P_v = f(\sin\delta)$ stabilizer (limited)	h	impulse response of the filter (limited)

From the mutual correspondence existing between each pair of the tabulated parameters it can be concluded that a computer program for the transient stability of co-operating power networks can easily be adapted for integrated digital (PCM) networks, too.

7. Conclusions

From statements in this paper the correspondence between the two networks under consideration seems to be proven. Adaptation of the computer program itself seems the author, however, to exceed the scope of this paper.

Summary

A new way of solving the synchronization problem of an integrated digital (PCM) network is described. Various bit synchronization methods are presented first, then mutually synchronized networks are discussed. Publications of one of the most important problems, i.e. transient stability are missing. Co-operating power networks are treated with special regard of their transient stability and a parallel is drawn between them both in mathematical and physical way. The conclusion is drawn that results for co-operating power networks can be applied for integrated digital (PCM) network as well, with appropriate modifications.

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