DYNAMIC STABILITY ANALYSIS OF LONG DISTANCE UHV INTERCONNECTION LINES USING SIMPLIFIED MODELS

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Received March 21, 1978

Presented by Prof. Dr. P. GESZTI

Introduction

The appearance of UHV transmission lines in bulk power interconnections opens an essentially new phase in the development of power system operation practice

Such UHV transmission lines are operated sometimes as tie lines between subsystems of big power interconnections. This sort of transmission lines can in some cases be of considerable length, as it is clearly demonstrated by the Soviet—Hungarian 750 kV line, which will be put into operation in 1978.

The basic role of such big power transmissions is to ensure the stable parallel operation of the systems interconnected. From this point of view, "stability of interconnection lines" can be spoken of — as a significant factor affecting the stability of the interconnected system as a whole. This concept is, however, rather undefined in itself, for "stability" in a more general sense is the property of a whole system: in the case of power systems, for instance, the following definition is widely used: — stability of a power system is the ability of its synchronous machines to maintain synchronous parallel operation during variable — normal or abnormal — operating conditions.

Consequently, one cannot speak about the stability of a part of the system in itself, because this is only one necessary condition of the stability of the system as a whole.

Nevertheless, the problem of power system stability in this general sense is hopelessly involved for practical computational purposes; it is indispensable therefore, to make some simplifications.

One possible way, for instance, of reducing the dimensions of the original problem is to study only the stability alone of the subsystems of the bulk power interconnection in question. The fundamental steps of this latter method are as follows: one has to select the very subsystem, the stability of which is of primary interest; all the power stations, network nodes and branches thereof are taken into account in detail, while the other subsystems are more or less reduced, depending on the degree of accuracy required.

While there are a great deal of practical possibilities to simplify the original system for studying its stability, there is one thing in common in all of them: creating a suitable model of the power system in question, a so-called "model system". This model system may consist of one subsystem represented in detail, with the other ones strongly reduced.

Concerning the UHV interconnection lines, it is easy to realize that they constitute a special type of subsystems. This sort of transmission lines are usually built of several sections and intermediate nodes, to which lower voltage networks and/or power stations are coupled through step-down transformers. UHV intersystem tie lines create a rather strong coupling among the power stations connected to their nodes; followingly that type of lines, together with the power stations mentioned, can be regarded as subsystems of the original power interconnection. According to this argument the rather vague concept of "the stability of UHV interconnection lines" can be put into a much concreter form: it becomes an approximation of the overall system stability problem, by which the UHV line, together with the electrically "near-by" power stations constitute the very subsystem represented in detail for stability studies, while the other parts of the system are significantly reduced.

In this way we get a special chain-formed model system for the stability studies of the UHV transmission in question, shown in Fig. 1.

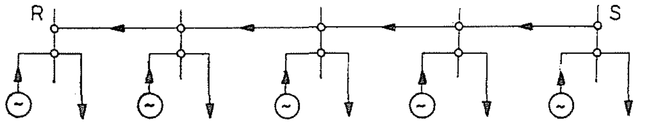

Fig. 1

By using the model system in Fig. 1 we can try to *answer the following questions*:

a) What is the maximum amount of active power, which can be transmitted through the UHV interconnection line in question, without the rupture of synchronism between the interconnected subsystems?

b) Among what type of circumstances can sustained — or growing — power oscillations take place on the transmission, which lead again to the rupture of synchronism?

c) What kind of perturbations — short circuits for instance — can cause transient instability between the subsystems?

The purpose of this paper is to analyze some aspects of the problems concerned in connection with the above *question* b) which is a special type of steady state stability; the American literature uses generally the term "*dynamic stability*" for this problem.

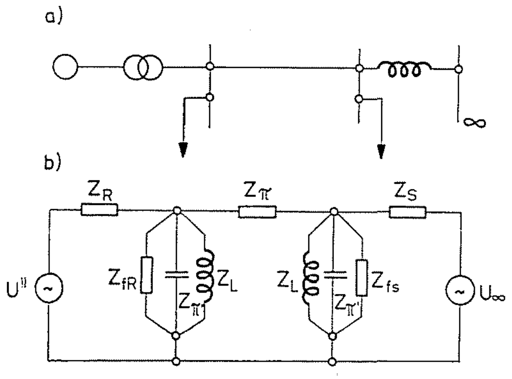

Fig. 2

The investigations are based on an even simpler model-system than that shown in Fig. 1: it is an improved and completed version of the well-known "one machine-infinite bus" model, and is seen in Fig. 2.

The UHV transmission line is modelled by the usual equivalent pi representation, and power is supposed to be transmitted always in S → R direction. The machine model near the node R represents a power station connected to the receiving-end substation through relatively small impedance Z_R. The sending-end system is supposed to have much more apparent power than the receiving-end subsystem, making thereby the infinite-bus representation "behind" impedance Z_s acceptable. The resultant load of both sides are represented by appropriate shunt impedances Z_f. Shunt reactors can also be taken into account Z_L.

The following investigations are based on the linearized state-space model of the system, shown in Fig. 2: linearization is admissible in this case, as the subject of the studies are small swings around prefixed operating points.

State equations of the model system in Fig. 2

For getting an appropriate state-space representation of the electromechanic system shown in Fig. 2, we have to start with the electric and mechanic equations of the alternator. It has been found practical to use Park's well-known reference frame to this purpose. To investigate the dynamic performance of this system, the electric transients of the rotor have to be taken into account, but in the case of solid rotors (as in our case) the exact formulation of the problem leads to extremely sophisticated, nonlinear relationships. Therefore, the usual practice is to represent the solid rotor effects by a number of fictitious rotor circuits in both directions d, and q. In the investigations described below the following rotor windings have been supposed:

— the field winding (subscript g)
— fictitious field winding in direction q (subscript gq)
— fictitious damping circuit in direction d (subscript ld)
— fictitious damping circuit in direction q (subscript lq)

(The voltage U" on side R — see Fig. 2 — is the so-called "subtransient voltage", the components d and q of which can be expressed as linear combinations of the below listed flux linkages.)

Neglecting the differential terms in the original stator-circuit equations of Park, four differential equations are arrived at describing the electric transients; they have to be completed with the second-order mechanic swing equation, for getting the "mathematical model" of the system studied.

These differential equations lead to a sixth order state-space model, to which the following state variables may be chosen:

δ the load angle
$\Delta\omega$ the speed deviation
$\psi_g, \psi_{gq}, \psi_{ld}, \psi_{lg}$ the flux linkages of the rotor circuits marked by subscripts.

(By omitting the differential terms in the stator-circuit equations we neglect automatically the direct current components caused by switching operations in the network, and with that the 50 cycles component of the electric moment; this is, however, permissible, as they have practically no influence on the small-swing dynamic performance of the alternator.)

The equations obtained can be linearized around the operating point ("equilibrium state") of the machine, applying the small perturbation theorem. Finally, the linear state equations of the model system is got in the well-known canonic form:

$$x = A\,x + \mathbf{B}\,u$$

$$y = \mathbf{C}x + \mathbf{D}\,u \tag{1}$$

where x is the state vector, u and y the input and the output vectors; **A**, **B**, **C** and **D** are matrices, the dimensions of which are determined by those of the former vectors.

In our special case these vectors are defined as:

$$x' = [\Delta\delta, \Delta\omega, \Delta\psi_g, \Delta\psi_{1d}, \Delta\psi_{gq}, \Delta\psi_{1q}] \tag{2}$$

$$u' = [\Delta U_g, \Delta U_\infty, \Delta P_t] \tag{3}$$

$$y' = [\Delta U_k, \Delta\omega] \tag{4}$$

where

U_g — field voltage
U_∞ — infinite-bus voltage
P_t — turbine power
U_k — terminal voltage of the alternator
Δ — means small variations around operating point

The elements of the above matrices can be derived on the ground of the Park equations (involving the neglects mentioned), and the node equations of the network in Fig. 2, not to be repeated here because of space shortage.

The structure of the matrices obtained finally is as follows:

$$\mathbf{A} = \begin{bmatrix} 0 & a_{12} & 0 & 0 & 0 & 0 \\ a_{21} & 0 & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & 0 & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & 0 & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & 0 & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & 0 & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & b_{22} & b_{23} \\ b_{31} & b_{32} & 0 \\ 0 & b_{42} & 0 \\ 0 & b_{52} & 0 \\ 0 & b_{62} & 0 \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ 0 & c_{22} & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$\mathbf{D} = \begin{bmatrix} 0 & d_{21} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The transfer function matrix among the defined inputs and outputs can be derived from Eq. (1):

$$\begin{bmatrix} \frac{\Delta U_k}{\Delta U_g}(s) & \frac{\Delta U_k}{\Delta U_\infty}(s) & \frac{\Delta U_k}{\Delta P_t}(s) \\ \frac{\Delta \omega}{\Delta U_g}(s) & \frac{\Delta \omega}{\Delta U_\infty}(s) & \frac{\Delta \omega}{\Delta P_t}(s) \end{bmatrix} = \mathbf{W}(s) = [\mathbf{C}[s\,\mathbf{U} - \mathbf{A}]^{-1}\,\mathbf{B} + \mathbf{D}] \tag{6}$$

where $\mathbf{U}$ is the unit matrix.

By substituting $j\omega$ for s in Eq. (6) one can get a suitable method for the point by point calculation of the Bode diagrams of any of the input–output pairs.

In the case of our model system there are two automatic control devices: the voltage regulator and the turbine governor of the turbine-generator unit. The input and output signals of the first one are the terminal voltage and the field voltage; for the second one these signals are the speed deviation and the turbine power output. It is obvious therefore that in our case the elements 1,1 and 2,3 of the transfer matrix in Eq. (6) are of primary importance.

Dynamic performance investigations: some results

The object of studies described below was a particular class of UHV interconnection lines, on which a significant amount of power is transmitted during normal operating conditions of the interconnected systems. In case of contingencies, however — resulting in power station shortage in the receiving-end system — the power transmitted may still considerably increase, and approach the stability limit value. The model system in Fig. 2 is especially applicable to qualitative dynamic performance studies of such kind of interconnections. (It is to mention here that the 750 kV line between Hungary and the Soviet Union will be of this type of interconnections.)

The main dates of the system studied were as follows:

rated line-to-line voltage: 750 kV
length of the UHV transmission line: 500 km
longitudinal impedance pro unit length: 0.013 + j0.27 ohm/km
transversal impedance pro unit length: —j0.25. 10^6 ohm/km
rated apparent power of the R power station: 1500 MVA.

The following "strategy" was chosen for the numerical investigations:

The operating conditions shown in Fig. 3 were taken as reference case; special computer programs helped to determine the "working point value" of the state variables, and afterwards the matrices of the state equations. The dynamic performance of the system — being in the shown (normal) operating condition — could be evaluated by determining the eigenvalues of matrix **A** and by computing the appropriate Bode diagrams.

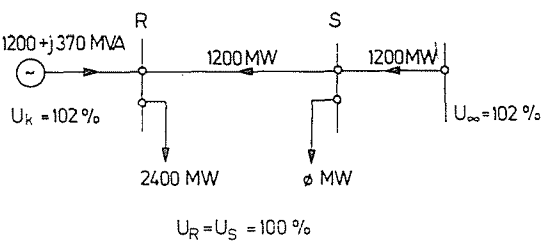

Fig. 3

In the second step a fully loaded 200 MW unit was supposed to fall out in the receiving-end system (this could be simulated by diminishing the turbine power in the model system by the same amount). The dynamic performance could again be studied in the same way.

Now repeating this step several times a state has finally arrived at, where a change of sign of the real part of one of the eigenvalues appeared, indicating dynamic instability. In this way the maximum transmittable power could simultaneously be determined.

Table 1

λ [1/sec]	P_{RH} [MW]
− 0.036 − 0.85 − 0.194 ± j5.43 −24.09 −26.26	0 × 200
− 0.22 − 0.68 − 0.19 ± j5.6 −24.24 −26.05	3 × 200
− 0.45 − 0.55 − 0.12 ± j5.61 −24.24 −26.05	6 × 200

The above procedure was easy to repeat with somewhat changed initial operating conditions or passive parameters, determining thereby the effect of the parameters changed on the dynamic performance of the system studied.

I should like to expound here only some of the most characteristic investigation results.

Table 1 shows the eigenvalues (2) of matrix **A** in the reference case, for lacks of power (P_{RH}) in system R of o MW, 3×200 MW and 6×200 MW, respectively. The first of the eigenvalues is "characteristic of the steady state stability" of the machine: this could be stated on the ground of former studies on the usual "one machine-infinite bus" model system (neglecting all the shunt impedances in the model of Fig. 2, and the machine supplying power to the infinite bus).

The results of these studies proved that the change of sign of the real eigenvalue mentioned above was simultaneously to that of the synchronizing power — which is a well-known criterion of steady state stability.

It is easy to realize that this very eigenvalue is getting more and more negative as the power deficiency increases on the side R (with the simultaneous increase of the transmitted power).

In the same time the real part of the conjugate complex pair of eigenvalues is getting less and less negative, as the transmitted power increases. Physically this can be interpreted as follows: the model system studied is getting nearer to the limit of dynamic stability (the damping of swings worsens), with the transmission line loaded more and more; the loading has, however, a contrary influence on the steady state stability of the system.

Table 2

λ [1/sec]	P_{RH}[MW]
− 0.111	
− 0.712	
− 0.14 ± j4.56	0 × 200
−23.77	
−25.45	
−0.29	
− 0.59	
− 0.11 ± j4.75	3 × 200
−23.84	
−25.38	
− 0.4	
− 0.63	
− 0.0091 ± j4.2	6 × 200
−23.88	
−25.39	

Table 3

λ [1/sec]	P_{RH}[MW]
+ 0.04	
− 0.75	
− 0.175 ± j4.62	0 × 200
−23.66	
−25.01	
− 0.027	
− 0.71	
− 0.16 ± j4.79	1 × 200
−23.69	
−24.98	
−0.35	
− 0.48	
− 0.104 ± j5.09	5 × 200
−23.89	
−24.79	

Concerning the effect of the reactances "behind" the buses R and S the following could be observed: increasing the reactance X_s (see Fig. 2/b) was favorable for the steady state stability, but diminished at the same time the damping of the system (i.e. the dynamic stability); this is seen from Table 2, showing the eigenvalues for this case. However, the increase of the reactance X_R had just the contrary influence on the stability of the system (see Table 3). It is interesting to note in this latter case that the first real eigenvalue is positive in base loading condition (i.e. with no lack of power on the side R), which

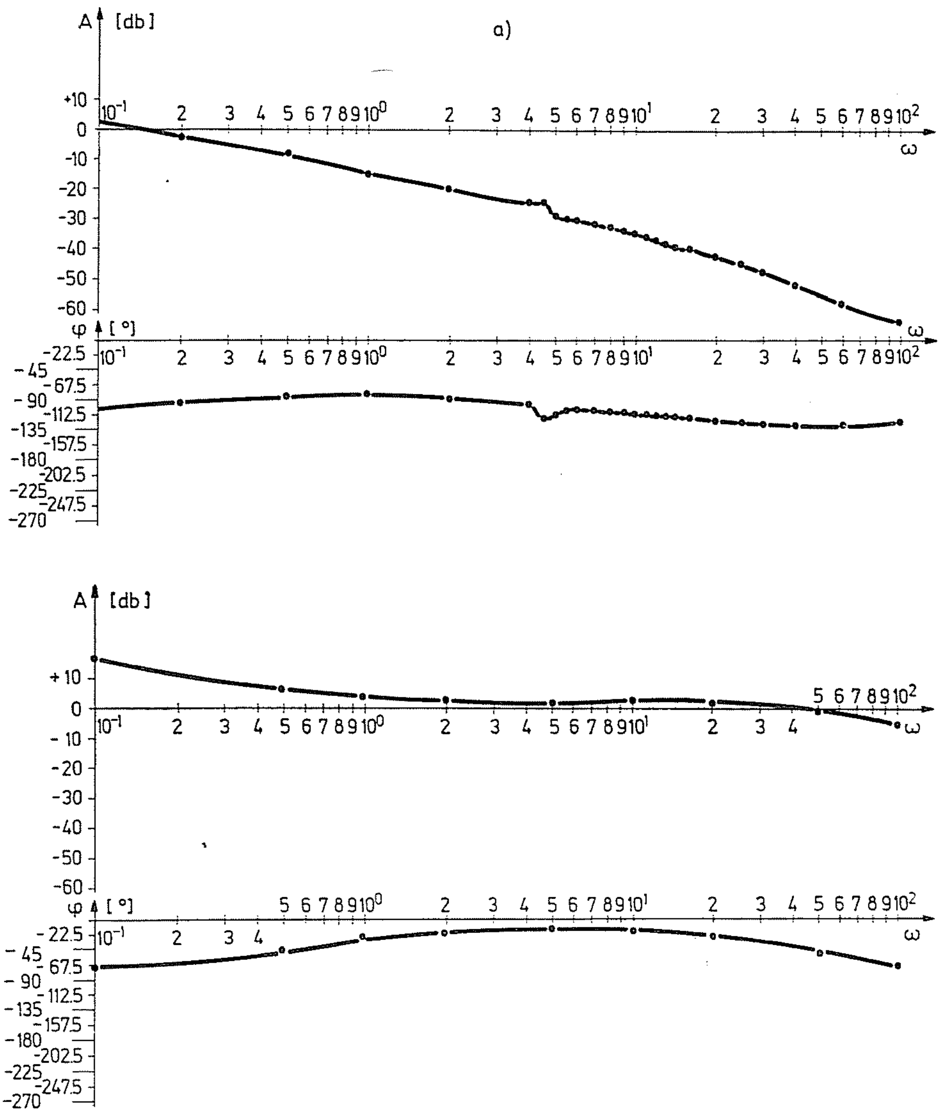

Fig. 4

means steady state instability in spite of the fact that the load angle is not more than 60°. The Bode diagram has, however, shown that with well dimensioned voltage regulator, steady state stability can be achieved, see Fig. 4.

Figure 4/a shows the Bode diagram of the system for this case, while Fig. 4/b that of a voltage regulator of usual structure and parameters. It is seen that the phase curve is going asymptotically to — 180° as ω tends to zero. Now comparing this with the Bode diagram of the regulator, it can be shown that stability — i.e. the counter-clockwise surrounding to the point -1 in the Nyquist diagram of the open-circuited regulation loop — can always be achieved, if the amplification of the regulator surpasses a certain minimum value.

All the above results were obtained with a nearly 100% shunt compensation of the line (which will be the case of the 750 kV Soviet–Hungarian interconnection line).

Supposing however, only 50% reactive shunt compensation — otherwise with the same parameters as in the reference case — steady state instability was found again in base load conditions (see Table 4). The physical explanation of this phenomenon is the relatively low excitation level of the machine, necessary for maintaining the same terminal voltage as in the reference case. (With voltage regulator the steady state stability could again be assured — according to the Bode diagram.)

In all the cases studied a marked deterioration of damping could be verified, as the lack of power increased on the receiving system: the real part of the complex conjugate eigenvalue pair (which was the only oscillating mode of the system) became less and less negative. In the case of Table 2, with 6×200 MW power shortage in the side R, it became practically zero — which means sustained oscillations and the limit of dynamic stability.

With further power lacking, instability (increasing oscillations) occurred, and voltage regulators of usual structure were insufficient to prevent it. (This is fully coincident with some former results, obtained with analog simulation techniques.)

Conclusions

The stability of UHV intersystem power transmission is an essential element of the stability — and thereby of the security — of the interconnected system as a whole. The problem in its original form is unduly involved, simplifications are therefore always necessary for practical purposes.

One extreme stage of simplification may be arrived at by the use of a specially completed "one machine-infinite bus" model system.

A possible linearized state-space representation of this model system is derived for dynamic stability investigations of the UHV power transmission in question. The studies were made by eigenvalue analysis and Bode diagrams.

In evaluating the results of the investigations, one must bear in mind the fact that the model applied is greatly reduced; first of all, it has only one mechanic degree of freedom. This fact hints to caution, and to take the results as first approximations only. However, some qualitative relations can be derived, with special regard to the influence of certain operating parameters of the system, such as for instance, loading conditions, reactances "behind" end-buses, degree of reactive compensation, etc. I should like only to point out two particular phenomena, which were otherwise ascertained by former investigations, too, namely:

— with the load of the UHV transmission line being equal to half (or less than) its characteristic power, there may be some steady state stability problem at power stations near the receiving end, if the degree of reactive compensation is low, and the voltage regulation of the machines is made by manual control;

— the maximum power which can be transmitted is first of all limited by the deterioration of the dynamic stability (damping) of the transmission; this can be prevented to a certain extent only by applying additional signals to the voltage regulators of the nearby synchronous machines, such as for instance their speed deviation or acceleration.

Summing up the results it can be stated that the dynamic stability of such power transmissions can be very favorably influenced by the suitable choice of the voltage regulator structure and parameters of the electrically "near-by" machines.

Summary

The stability of UHV power interconnection lines is an essential element of the stability of the interconnected system as a whole. The paper presents a special form of system simplification, which can be used in studying the steady state and dynamic stability of the interconnection.

The principle of the studies is described, and some numeric results are given concerning the possibilities of improving the dynamic stability of the power transmission in question.

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