Stability of Ultra Long Distance AC Power Transmission Lines with Controlled Shunt Compensation Devices

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***Abstract*— An overview of AC and DC transmission systems in China has been made and it is shown that many DC transmissions from 2500 to 4400 km can successfully be substituted by AC ones with certain set of controlled shunt compensation devices. Investigations of operating conditions and small signal stability for ultra long-distance power transmission lines as well as analysis of transient processes have been carried out. It is shown, that parallel operation of controlled shunt reactor and synchronous compensator at one node significantly expands the range of possible line lengths and allows the implementation of power transmission modes close to surge impedance power. A special line property, associated with impossibility of long line operation only with static compensation devices, at full angle of transmissions larger than 180 electrical degrees, does not appear in such a scheme.**

Keywords—interconnections; small signal stability; FACTS; controlled shunt reactor; synchronous generator; synchronous compensator; long-distance transmission system

I. Introduction

Recently, the problem of expanding production of electric energy in places with a large concentration of hydro, heat and non-traditional energy resources, which, as a rule, are remote from consumers for considerable distances, up to several thousand kilometers, becomes urgent in the power system of China (Fig. 1). All these projects require a perfect, economically feasible and environmentally safe technology for transmission of electrical energy over ultra long distances. Various scenarios of direct (±800 and 1100 kV) and alternating current (1000 and 1200 kV) line construction are equally considered.

As it is known, DC transmission does not require installation of reactive power compensation devices on lines. However, to ensure conversion from AC to DC and vice versa, at both sides, controlled reactive power sources are needed. In addition, the costs of installing and maintaining converter devices are comparable to the cost of constructing lines.

The significant difference in charges on end devices of AC and DC lines is particularly significant if one takes into account that power delivery at intermediate points of line requires installation of converter devices at each of these points with a corresponding significant increase in costs. Gradual development of industry in China implies the emergence of large clusters of consumers not only along the coast of East China Sea, but also inside the country. In this case, there will be a need for a significant power delivery at the intermediate points of transmission systems.

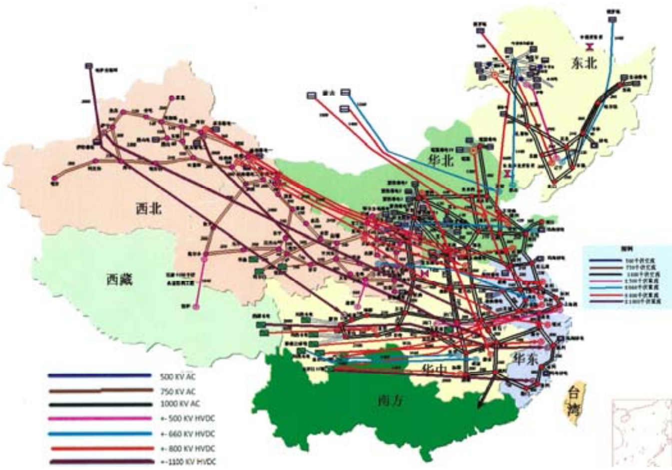

Fig. 1. China extra high voltage 2020 grid plan [1]

As compensation devices, synchronous compensators (SC), controlled shunt reactors (CSR), static var compensators (SVC), superconductive magnetic energy storage devices (SMES) and their combinations could be used [2, 3]. Application of these reactive power compensation devices is expedient in conjunction with measures to improve the design of overhead lines, such as creation of increased surge impedance lines [4].

II. LONG DISTANCE AC TRANSMISSION LINE MODELING

The investigations are carried out for power transmission model shown in Fig. 2. Design scheme consists of equivalent generator operating in parallel with an infinite bus receiving system through long-distance 1150 kV AC power line modeled by chain structure. Power transmission capability of this line when using high surge impedance loading (SIL) construction is 7 340 MVA. Controlled shunt compensation devices (CSCD) are installed at intermediate points of the line that support voltages within specified limits and provide a balance of reactive power in wide range of power transmission (from zero to SIL). As such devices, controlled shunt reactors, synchronous compensators, and also their joint operation in one node are considered. All transformers are supposed to be ideal.

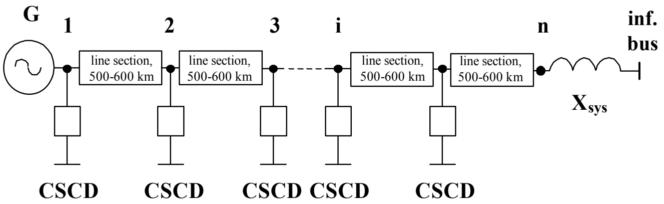

Fig. 2. Model of ultra long distance power transmission system

The estimation of quality of transient processes is based both on analysis of time dependencies of operation parameters obtained from numerical integration of nonlinear differential equations system consisting of typical mathematical description and also on the basis of state matrix eigenvalue analysis of linearized equations.

III. STABILITY OF TRANSMISSION SYSTEM WITH CSR

At the first stage of study, only CSR are used as CSCD, control system structure of which is shown in Fig. 3. As input parameters of CSR control, voltage deviations at reactor bus is used as well as voltage frequency and its derivative.

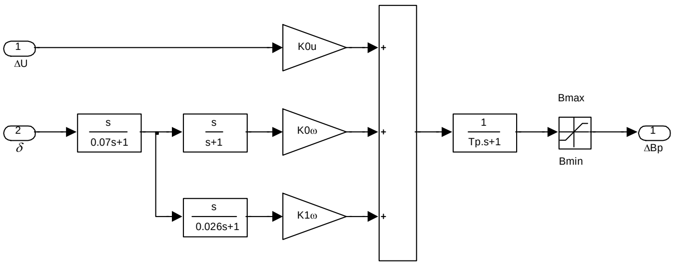

Fig. 3. CSR control system

Table 1 shows the operating transmission limits and total angles corresponding to these conditions, depending on line length, as well as dominant system eigenvalues.

Increasing the length of line, according to small signal stability analysis, results in reducing transmission limits, which becomes less than surge impedance loading from 2000 km length. The reduction of active power transfer becomes particularly noticeable at line lengths above 2400 km, caused by approaching the total angle of transmission to 180 degrees. It is not possible to reach substantially larger values of angles for any feedback setting of CSR and AVR/PSS control systems. The only exception is limit of power transmission along a 2400 km line, in this case, δ = 184.16 degrees, while nature of transient process, caused by small disturbance of equivalent generator power, is changed considerably.

When using only CSRs as compensation devices, the limit is imposed on operations of long line by maximum total angle, which can not exceed 180 degrees, because of self-excitation appearance [5]. This leads to significant reduction in ultimate capacity with increasing line length. Even with line lengths exceeding 2500 km, maximum transmitted power becomes unacceptably low, and economic efficiency of such transmissions is substantially reduced.

It is known that application of synchronous compensators with natural internal EMF and mechanical inertia can solve this problem. Even when SC is not installed at all intermediate points, but at a distance of 1500-2400 km, a special property of line does not appear.

TABLE I. STABILITY LIMITS OF TRANSMISSION SYSTEM WITH CSR

Line length, km	P_{lim}, p.u.	Dominant eigenvalues	δ_{lim} (δ_{line}) el.deg.
1400 3 sections	**1.0**	-1.251 ± *j*0.453 -0.443 ± *j*0.233 -0.455	**140.47** (83.46)
1600 3 sections	**1.0**	-0.871 ± *j*0.388 -0.542 ± *j*0.254 -0.459	**151.5** (94.48)
1800 3 sections	**1.0**	-1.162 ± *j*0.409 -0.417 ± *j*0.235 -0.441	**162.52** (105.5)
2000 4 sections	**0.97**	-0.498 ± *j*0.44 -0.595 ± *j*0.127 -0.479	**168.9** (116.8)
2200 4 sections	**0.97**	-0.219 ± *j*0.144 -2.66 ± *j*0.160 -0.487	**179.22** (127.6)
2400 4 sections	**0.94**	-0.295 ± *j*0.483 -0.529 ± *j*0.135 -0.441	**184.16** (129.3)
2600 5 sections	**0.84**	-0.594 ± *j*0.549 -0.466 ± *j*0.0965 -0.447	**177.84** (125.6)

a. oscillation frequencies are given in Hz

The scheme proposed in [6] for operation of two controllable devices (SC and CSR) at one point allows to reduce SC installed capacity significantly. Reactive power of compensator can technically vary within its capacity, both for delivery and consumption. When SC is connected in parallel with CSR, it operates with E_{Qc}=1 p.u., i.e. at zero reactive power output, and its key functions are transmission stability maintenance and oscillation damping. Consuming excess reactive power generated by the line is taken over by controlled reactor, which changes its conductivity, depending on current conditions. If SC AVR/PSS and CSR control systems are correctly set up together, SC should remain in zero power output mode after any disturbance.

IV. Stability of Transmission System with CSR and SC

Features of parallel operation of SC and CSR at one point, analysis of joint operation of CSR and SC AVR/PSS control systems as well as choice of admissible values of feedback settings are considered using the example of model shown in Fig. 4. Long-distance line up to 2200 km length is modeled by four identical sections. The choice of line length is due to the fact that total angle in this case is close to 180 degrees for powers of 90-100 % of surge impedance loading. At such a sufficiently long length, all features of long-distance line are fully appeared, and at the same time, selecting all control parameters is possible in a wider range than with a longer line length. Controlled shunt reactors are installed at power plant bus, as well as at nodes 2-4, in addition, an equivalent SC is installed at node 3. The reactive power supplied by generator to the network is selected both from calculation of maximum possible one, depending on active power transmitted through the line, and based on the need to provide maximum stability margin, with minimum possible output of reactive power to the network.

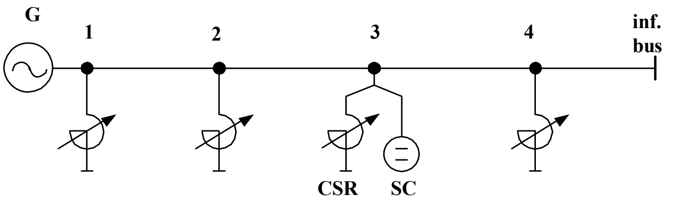

Fig. 4. Model of 2200 km AC transmission system

Investigations of transient processes in the system caused by small disturbances on turbine torque (1-3% of total capacity) reveal real impact of SC PSS frequency deviation feedback on damping and frequency of electromechanical oscillations (optimum value of $K_{0\omega c}$=3…5). The effect on damping of first derivatives of voltage and frequency is appeared in lesser degree (optimum values $K_{1\omega c}$=5…10 and K_{u1c}=-10…-15). The function of voltage deviation feedback is to maintain the voltage at SC bus within specified limits (optimum value is K_{0uc}=-30…-50).

With relatively short lines, it is possible to implement co-regulation at node 3 of SC and CSR equipped with a control systems of abovementioned structure, but for line lengths longer than 3300 km there is a conflict between compensator and reactor control systems caused by using the same operation parameters: voltage deviation, frequency deviation and first derivative, expressed in occurrence of electromagnetic instability at a frequency of about 10 Hz. Disabling CSR control of reactor at node with SC allows to solve the problem of occurrence of high-frequency undamped oscillations, and this conditions of transmission will be stable. However, as mentioned above, application of uncontrolled reactors is unpractical, so it is necessary to control CSR inductance by other operating parameters than in AVR/PSS of synchronous compensator, for example, line current, active power, etc. Since the main feedback of any synchronous machine is voltage on its stator bus, shunt reactor can be controlled by deviation of total line current. Fig. 5 shows block diagram of proportional single-feedback regulator of CSR.

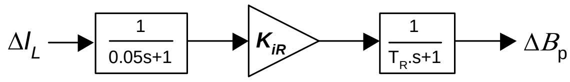

Fig. 5. Diagram of proportional CSR control system

The value of reactor feedback gain by deviation of total line current K_{iR} is chosen from consideration that change in reactor conductivity should be the same as corresponding change in conductivity in case of traditional control, after same disturbance. Otherwise, there is an imbalance in reactive power distribution between SC and CSR. With an increase in absolute value of K_{ip}, the SC has to switch to operation of consuming a sufficiently high reactive power. This is due to the fact that conductivity of reactor is deeply reduced with large settings of CSR proportional feedback.

Since total current of compensation devices is determined on the basis of each particular condition, when reactor current is changed much more than required by new steady-state operation, SC is forced to consume such a reactive current in order to compensate for this change. With insufficient value of the CSR control setting by deviation of total line current, a reverse trend is observed. SC switches to operation of delivering reactive power to the system, in order to compensate for reduction in CSR conductivity, which is necessary under new conditions, which, due to small value of K_{ip}, is insufficient. With the optimum selection of K_{ip} value, SC in new steady-state operation should return to zero consumed reactive power mode, however, choice of such a value of K_{ip} is difficult. In addition, in real power system, all small disturbances, as mentioned above, are random in nature and sign, therefore, the optimum value of K_{ip} for each particular disturbance will be different.

It is possible to solve the problem of CSR and SC operation coordination at one node by introducing an additional control feedback in reactor control system by one of SC parameters. As such a parameter, the stator current in direct axis of SC i_{dc} is chosen. Implementation of other parameters is not appropriate, or leads to transmission instability. The structure of this control feedback is the same as it is given at Fig. 5, time response T_{idR} is equal to 5 sec. [7], a lower value of feedback setting led to instability is equal K_{idR} = 0.5.

A similar or even greater effect can be achieved by using in SC AVR/PSS an additional feedback of at least one CSR parameter, for example, deviation of reactor current in direct axis i_{dR}, whose value under operation is not difficult to obtain by adding computing element in CSR control system. The structure of this control feedback is also the same as it is given at Fig. 5, parameters are chosen as follows: K_{idc} = 5, T_{idc} = 1...5 sec.

Fig. 6 shows an example of impact of additional SC control feedback and the joint effect of additional control feedbacks in SC and CSR on the value of SC reactive power Q_{sc}, after transition to new steady-state operation.

It should be noted that there is a significant influence of SC mechanical inertia on the nature of transient processes. When decreasing inertial parameter T_{jc}, at constant installed capacity, the frequency of dominant electromechanical oscillations of SC rotor increases, with simultaneous deterioration of this component damping, until oscillation instability. It is small value of T_{jc}, and not small value of SC installed capacity, is responsible for oscillatory instability of the system at frequency of electromechanical SC rotor oscillations (1-2 Hz). An increase of mechanical inertia T_{jc} leads to decrease in dominant frequency of oscillations and improve in damping of this component.

In conditions of real operation, for typical machines of low rated power, it is technically not difficult to increase SC mechanical inertia by fixing additional masses on rotor. At the same time, it is known that such a result can be achieved by accepting additional feedbacks of excitation control [8]. With correct joint coordination of the SC and CSR control systems, further reduction of SC installed capacity is possible, with values of T_{jc} remaining at level of 2-5 sec. In this case, it could be needed to increase values of active resistances of SC amortisseur windings, which will allow to reduce value of T_{jc} without loss of system stability.

a)

b)

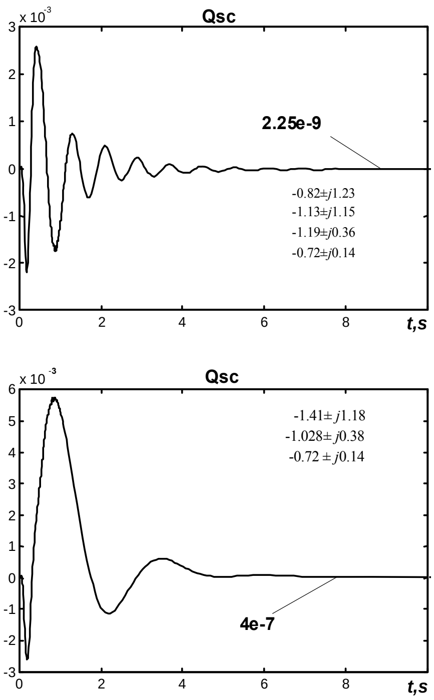

Fig. 6. Transients caused by step increase in turbine torque, when generator is operating through 2200 km line, modeled by 4 sections, to infinite bus, in case of using CSR at nodes 1-4 and SC at node 3. Initial operation is P=0.9 p.u., Q=0.2, ΔP=0.01, Q_{SC}=0. CSR parameters: K_{0uR}=-20, $K_{0\omega R}$ =3.0, $K_{1\omega R}$=1, T_R=2 sec. SC parameters: K_{0uc}=-30, K_{u1c}=-15, $K_{0\omega c}$=5, $K_{1\omega c}$=10, K_{ifc}=-0.3 *a) with additional feedbacks in CSR and SC control systems; b) with additional feedbacks in SC control system*

However, control range limits of SC are reduced, and then the key advantage of SC to change its loading at reactive power, within its nominal capacity, both towards consumption and delivery, is lost. Therefore, it is advisable to take SC installed capacity within the range of 5-10 % of surge impedance loading, based on a typical values of nominal capacities: 25, 50, 100, 160, 320 MVA.

Analysis of stability limits for lines with CSR and SC as compensation devices is also carried out for model shown in Fig. 4. In the middle of line, regardless of length, a synchronous compensator running parallel with CSR is installed. The number of required sections, depending on the length of the line, is determined as follows: from 1200 to 2400 km – 4 sections, from 2400 to 3600 km – 6 sections, from 3600 to 4800 km – 8 sections. With increase of line length, small signal stability limit decreases, and, starting at 1900 km, becomes less than surge impedance loading. Decreasing the limits becomes especially noticeable at line lengths exceeding 4200 km, which corresponds to 2100 km between equivalent generator and SC, SC and infinite buses, that is, between elements having a natural internal EMF. At such a length, special line features with only static compensation devices are appeared, namely: a noticeable decrease in active power transmitted through the line followed by increasing line length; necessity of diminishing gains of all CSR control feedbacks. Up to line length of 3400 km, maximum transmitted power differs a little bit from the value of about 0.93 p.u., while total angle in transmission increases. The values of active resistances of SC amortisseur windings are chosen on the basis of ensuring sufficient damping of oscillations.

Stability limits could be increased substantially by reducing the distance between nodes with SC. When compensator is installed in parallel with reactors at nodes 3, 5, 7, that is, other nodes are only equipped with CSR, for a line length of 4400 km maximum transmitted power is increased up to 0.92 p.u. In this case, transmission distance between elements with internal EMF does not exceed 1500 km, and the properties of long-distance line are largely determined by length of this section. This circumstance makes it possible to increase the value of active power transmitted through line.

TABLE II. STABILITY LIMITS OF TRANSMISSION SYSTEM WITH CSR/SC

Line length, km	P_{lim}, *p.u.*	*Dominant eigenvalues*	δ_{lim} (δ_{line}) *el.deg.*
3400 6 sections	**0.93**	-0.276 ± *j*0.882 -0.834 ± *j*0.319	**232.08** (176.98)
3600 6 sections	**0.91**	-0.14 ± *j*0.837 -0.911 ± *j*0.272	**236.36** (181.85)
3800 8 sections	**0.88**	-0.286 ± *j*0.983 -0.921 ± *j*0.290	**240.91** (187.31)
4000 8 sections	**0.87**	-0.272 ± *j*0.978 -0.812 ± *j*0.369	**247.02** (193.73)
4200 8 sections	**0.85**	-0.222 ± *j*0.968 -0.793 ± *j*0.362	**250.0** (197.47)
4400 8 sections	**0.8**	-0.219+j0.979 -1.413 ± *j*0.269	**244.26** (193.28)
4600 8 sections	**0.78**	-0.339 ± *j*0.937 -0.969 ± *j*0.315	**245.81** (195.56)
4400 8 sections SC at nodes 3, 5, 7. S_{sc}=320 MVA	**0.92**	-0.252 ± *j*0.714 -0.761 ± *j*0.993 -0.464 ± *j*0.95	**276.45** (221.64)

In conclusion, it should be noted that proposed scheme of parallel operation of two controllable compensation devices (SC and CSR) has the following essential features:

1. it has all the advantages of both devices and partially eliminates the shortcomings of each individually, performed on the basis of standard power equipment, at relatively low cost and low SC installed capacity;

2. it essentially extends the range of possible operating conditions of long-distance AC transmissions and makes control more flexible.

From the energy point of view, SC installation is minimal solution, therefore obtained results can be generalized to the application for these purposes of power plant generators with relatively low capacity. In this case, generator, in addition to oscillations damping function, can also compensate losses of active power in long-distance transmission. The function of excess reactive power consumption is applicable to controlled shunt reactors [9]. In conditions of power transmission, which is higher than surge impedance loading, generator could provide necessary reactive power to the network. This allows to use low-power plants, after appropriate enhancement, when constructing ultra-long-distance interconnections, instead of building new substations. All abovementioned could become economically effective in conditions of dynamically emerging market of China.

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