TRANSIENT STABILITY IMPROVEMENT OF EHV POWER TRANSMISSIONS BY ADAPTIVE SINGLE-POLE RECLOSING

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Received Okt. 22, 1984
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Summary

Some special aspects of the stability properties of EHV power transmissions are pointed out in the introduction, followed by a more detailed analysis of the impact of single-pole short circuits and automatic reclosing. Digital investigation results are described, on ground of which critical reclosing dead-time values are established in function of the pretransient power transfer and other relevant parameters.

The advantages of adaptive single-pole reclosing method are stressed for increasing the chances of preserving synchronism, and "probability of transient stability" values calculated, which clearly show the favorable effects of said method on the transient stability levels of EHV transmissions.

Introduction

EHV transmission lines (i.e. those with a rated voltage of 400 kV and above) are used more and-more for the interconnection of big power pools and/or national power grids. (As an example the Soviet-Hungarian 750 kV interconnection line is worth mentioning, along with some EHV lines between the USA and Canada; other ones are being constructed in Latin America and elsewhere.) The reliable operation of EHV tielines influences considerably the security of the power systems interconnected by them, since their outage due to short circuits or other failures may lead to the splitting up of the whole power interconnection into several subsystems. If in anyone of these latter there is significant power deficit (or power excess), then the prevention of total system collapse may prove a rather difficult task for the dispatching personnel of said subsystems.

It is easy to realize, further that once such a transmission line has been put into operation, the electrical distances among power stations of different subsystems may become much shorter, than before.

This circumstance affects considerably the stability performance of the whole interconnected system.

In this context the following stability problems may appear:

1. What is the limit of power, which can be transmitted through a given EHV interconnection without the loss of synchronism between the subsystems on both ends?

2. In what circumstances may persisting power swings show up on said transmission line, endangering the stable operation of the system as a whole?

3. What type and magnitude of disturbances may bring about transient instability between the subsystems interconnected by the EHV line in question?

In this paper a special aspect of the latter problem will be analyzed.

Power system engineers are well aware of the fact that the class of disturbances being most dangerous for the transient stability of long distance power transmissions is that of shunt faults. Furthermore, of all sorts of shunt faults three phase short circuits are the worst ones from point of view of stability. Fortunately, they make up in general less, than 10% of all short circuits according to operational statistics.

In the meantime monophase short circuits are by far less dangerous, however they are in overwhelming majority within all shunt faults recorded: more, than 85% of these faults are single phase short circuits.

As nowadays practically all transmission line protections are equipped with fast reclosing function, it is clear that the "most attractive" type of said disturbances are single-phase short circuits with successful single-pole reclosing. Actually, in case of not exceptionally long (i.e. below 5–600 km) EHW power transmissions they are far from being crititical, if the pretransient power-transfer has been in the *medium load-range*. Moreover, even single-phase short circuits with unsuccessful single-pole reclosing do not affect seriously the transient stability of said EHV transmissions.

However, as soon as pretransient load exceeds 70–75% of the surge impedance power, even monophase short circuits may prove critical, and the *length* of reclosing *dead-time* becomes the main influencing factor as far as transient stability is concerned. Of course unsuccessful reclosing is highly undesirable in such cases, therefore protection engineers are doing their best to prevent this unwelcomed phenomenon. Now the well-known condition of any automatic rapid reclosure for being successful, is that the secondary arc extinguishes (and the arc-path is deionized, this latter occurring normally well within 50 msec) before the closure of the main contacts of the circuit breaker. Unfortunately, secondary arcing times measured in single-pole reclosing field tests have shown considerable scattering around the average value, which means relatively high standard deviation (σ). (This fact is due to greatly varying physical factors affecting the endurance of the secondary arc.)

It is easy to realize that system operation and protection personnel wants to be on the safe side, consequently the usually applied single-pole reclosing dead time values lie in the range of $3 \cdot \sigma$ above the mean, or possibly a bit above the longest secondary arcing time measured in anyone of the field tests, with a suitable safety margin.

Said circumstances explain the fact that in most of the industrialized countries single-pole reclosing dead times used fall in the range of 1.5–2 sec. Meanwhile, according to monophase short circuit field test results obtained by several private or state-owned electric utilities at least 90% of all secondary arc extinguishing times measured are below 0.8 sec.

Translated into stability terms this means that under heavy load conditions the transient stability of EHV transmissions is seriously endangered by long single-pole reclosing dead times, only because in exceptionally unfavorable circumstances secondary arcs may last some 1.5–2 seconds. The problem is especially acute in those cases, when said transmissions are used up to their steady state power transfer capability limits, which is not at all a rarity: in fact, economy considerations require that such big installations be fully used as long and as many times as possible within their useful life. For such EHV lines monophase short circuits mean in most of the cases transient instability because of the "safe-long" dead times, whereas synchronism would easily be preserved, could the circuit breakers be *reclosed* by any means *immediately after* the *extinguishing* of the secondary arc.

P. O. Geszti and his co-authors presented a paper [1] at the 1982 CIGRE Session in Paris, which dealt with some problems of single-pole reclosing in EHV/UHV lines. In this paper they proposed a method, suitable to indicate reliably and accurately the extinguishing of secondary arc; moreover, they presented a device, which on ground of said method could trip automatic reclosing; they called their method "adaptive single-pole reclosing".

To point out the significance of such a technique let us regard things a bit from the probabilistic side:

Up to now system protection engineers have been faced with the following dilemma:

- — either to adjust single-pole reclosing dead times lower (around the expected mean value, i.e. about 0.7 sec.), and this way run a certain risque (appr. 10–15%) of unsuccessful reclosing with all its drawbacks (including a good chance of losing synchronism);
- — or to use the mean $+3 \cdot \sigma$ value, and then to put up with an almost certain transient instability following monophase short circuits, whenever the EHV line is loaded near the steady state limits.

The "adaptive single-pole reclosing" technique proposed in the above mentioned paper (and tried successfully since then) eliminates said dilemma, and permits an acceptably low risque ($1 \sim 5\%$) of losing synchronism even in heavy load conditions, without any danger of reclosing into short circuits.

To explore the possibilities of improving "probability of transient stability" by this (or similar) adaptive single pole reclosing scheme, the relation

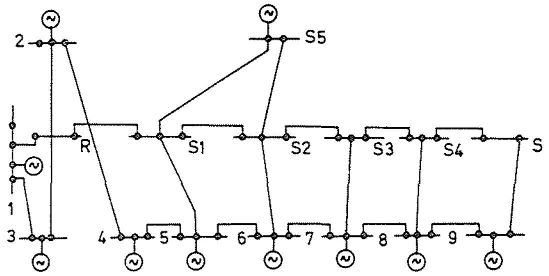

Fig. 1

between permissible dead time and pretransient loading conditions has to be analyzed.

Some interesting results of such numerical investigations will be given below, made for the same existing EHV power transmission as discussed in a previous paper of the author [2]. 0.1 sec monophase short circuit clearing time has been assumed throughout the studies, which is usual with modern (but not very high speed) protections and circuit breakers.

The model system used is shown in Fig. 1. on the S side a fictitious unit of practically infinite inertia has been represented to prevent load angle drift during the transient processes. The following pretransient load states (of the EHV transmission) have been examined:

a) 85% of surge impedance load (in the S1-R section, see Fig. 1;
b) 90% of surge impedance load
c) surge impedance load (which was 2150 MW)

For the limiting values of single-pole reclosing dead time (i.e. those resulting in transient stability limit case) the following have been obtained:

ad a) 2 sec
ad b) 0.9 sec
ad c) 0.4 sec

It is not difficult to observe the tendency of relation between pretransient load and dead time limit (see Fig. 2.) With loads below 80% of the characteristic power we expect, accordingly that dead time becomes irrelevant (in other words: synchronism can be maintained even with one pole of the circuit breaker kept open indefinitely). (This has been proved by another study.)

In Figs 3 and 4 some of the oscillation patterns obtained are shown. The former is related to case b) with 0.83 sec dead time, i.e. slightly below the limit value: swings of decreasing amplitude can be observed. The latter is the same case, but with 1.15 sec dead time, i.e. beyond stability limit: transient instability ensues visibly through swings of growing amplitude. This is quite unusual, since in general type power system studies the rupture of synchronism comes

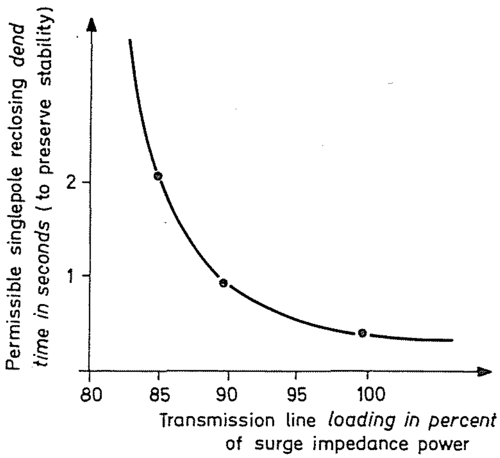

Fig. 2

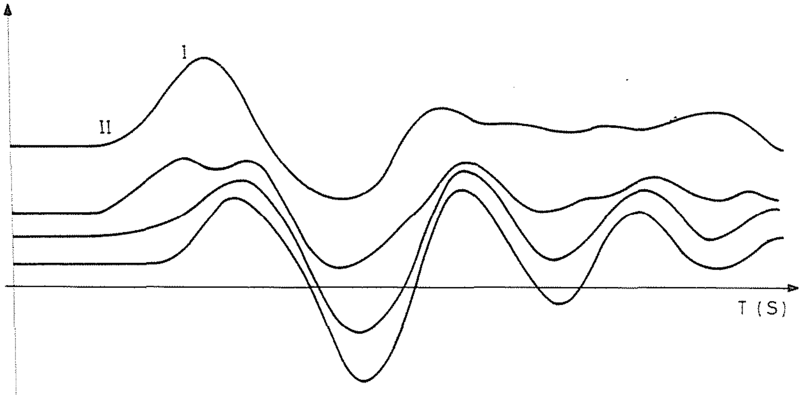

Fig. 3

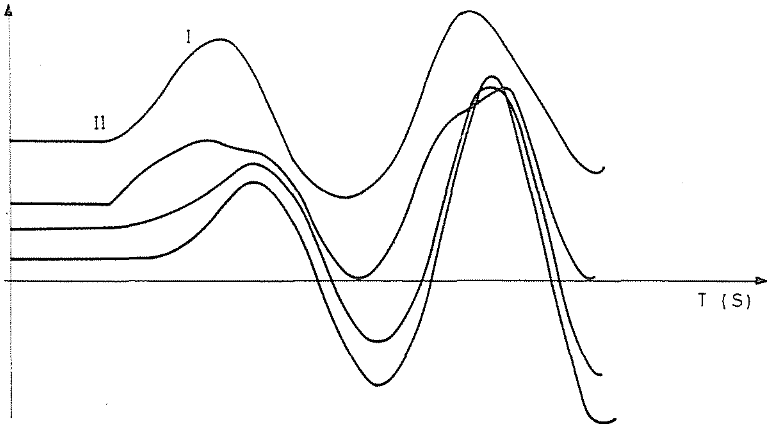

Fig. 4

about usually in the first swing, which may be explained physically by excess of kinetic energy, on ground of Liapunov's direct method.

Here, however, this explanation does not work. The reason for said "periodic instability" had been explained in reference [2] and [3]. It has been demonstrated there that in heavily loaded conditions of long, EHV power transmissions the real part of the mechanical-mode eigenvalue may become positive. The analog studies discussed in ref [2] and [3] have equally shown oscillations of growing amplitude above definite load level, which were in agreement with said positive eigenvalue.

Now the reason for periodic transient instability is that if the perturbation magnitude exceeds certain limit, the resulting transient load angle differences (and along with that the terminal node voltage decrease) may reach into that range, where damping becomes negative, and brings about transient instability through growing swings. (The size of the disturbance was measured here by the length of dead time applied.) A further growth of the dead time has led to still bigger excess kinetic energy, which provoked instability in the usual way (i.e. during the first negative swing amplitude for the receiving end machines.)

Consequently, in case of EHV/UHV power transmissions (or put in more general form: in longitudinal-structured EHV/UHV subsystems) the transient stability range, and the first-swing type instability range are separated by an *intermediate domain*, characterized by instability due to *negative damping.*

Along with said stability investigations a qualitative check has been made for the same EHV power transmission, using the simplest model possible; namely representing all the S-side units by one equivalent synchronous generator, and all the R-side ones by a single synchronous motor. These machines have been interconnected by an equivalent reactance. Using equal area criterion and precalculated swing curves the calculations have bee carried out on a programmable pocket computer.

The same loading conditions were supposed as above. Permissible dead time values were calculated for all the three cases mentioned before, and the results arrived at lay quite close to those given above, whenever the rated power of both R- and S-side equivalent units were taken as two and a half times the surge impedance load of the EHV transmission studied.

Actually the results were slightly optimistic, compared to those obtained by digital simulation, but the errors have never been more, than 15%. (The calculation results are shown in Table 1.) This shows that even the most simple classic equal area method along with precalculated swing curves might sometimes be justified for quick (qualitative) stability checks, using the most modest computational means available.

In these simplified calculations each of the receiving and sending-end short circuit reactances have been assumed to be 0.3 p.u. related to the rated

Table 1

Single-pole reclosing — critical dead-time values (sec)

Pretransient power (MW)	*Line length*: $\frac{1}{12}$ wave-length		$\frac{1}{8}$ wave-length	
	power proportion: 2:1	3:1	1:1	2:1
1250	whatever	whatever	whatever	whatever
1300	whatever	whatever	whatever	1,3
1450	whatever	whatever	whatever	0,62
1600	whatever	whatever	whatever	0,36
1820	1	1.15	0.7	0.096
2000	0.5	0.58	0.27	unstable (with zero)
2200	0.31	0.38	0.16	unstable
2400	0.14	0.16	unstable	unstable
2460	0.09	0.1	unstable	unstable

power of the fictitious R- and S-side units respectively, which, in turn, were taken as 2.5 times the surge impedance load of the EHV-line in question (see above).

The effect of the lower voltage networks being in parallel to said EHV transmission have been represented as shunt impedances, the value of which was varied in three steps. Accordingly, three different power distribution relations could be considered in pretransient state between the EHV-line and the lower voltage parallel network:

2:1, 3:1, 1:1, each related to the power flowing through the former one. From these values the first one seems to be the most realistic.

The investigations have been carried out for two different EHV line-length: 500 km and 800 km (again the first one is which occurs more frequently in the existing EHV transmissions all around the world).

Table 1. shows the critical dead-time values obtained for different transmitted power values in the cases mentioned above. The clearing time has been assumed 0.1 sec uniformly in all of the studies.

On ground of the table the following conclusions can be drawn:

a) If the power transferred through the EHV transmission in pretransient state does not exceed 1250 MW (i.e. about 60% of the surge impedance load), then stability can be maintained with whatever long single pole reclosing dead time, in all the three cases studied.

b) For a line length not more than 500 km the load limit value (below which single pole reclosing dead time is irrelevant) is 1600 MW (i.e. about 70% of the characteristic power).

c) For 800 km line length (or above) monophase short circuits result in transient instability with whatever short dead time values, if the pretransient load is more than 1900 MW (or 86% of the surge impedance power).

d) For EHV transmission lines loaded by the characteristic power and not longer than 500 km the transient stability can be maintained, if the single pole reclosing dead time does not exceed 0.16 sec.

This is true for practically whatever proportion of lower voltage shunt network connections.

There are several single pole reclosing field test results reported in the literature, with rather different secondary arc extinguishing times measured. Some of them will briefly be reviewed below.

1) The American Electric Power Co. reported the following three field test results obtained for the secondary arc extinguishing time:

0.742 sec.
0.725 sec.
0.758 sec.

The average of the aobve values is: 0.742 sec, while the standard deviation: 0.0134 sec.

2) The Bonneville Power Administration published eight test results, obtained similarly for natural secondary arcing times. The average value was: 0.52 sec., the standard deviation: 0.25 sec. (i.e. the results had been dispersed much more, than the AEP ones).

3) The Tenessy Valley Authority obtained several years earlier 9 successful single-pole reclosing out of 11 field tests; the average dead-time was 0.4 sec, with negligibly small standard deviation. In the tests no neutral reactors were applied. If normal distribution law is assumed for the secondary arcing time, this means that the mean value plus standard deviation would be 0.4 sec approximately.

4) A CIGRE Report dealing with single-pole reclosing test results informed about quite a number of arc extinguishing time measurements; in the majority of these tests secondary arc current was in the 10–50 A range (44 measurements). The average value obtained was: 0.279 sec. with standard deviation being as high as 0.181 sec.

5) According to some soviet results roughly in half of the field tests (in 12 cases) the secondary arc current measured fell in the 10–60 A range, having secondary arcing time average value of 0.228 sec; the standard deviation was 0.083 sec. (In said tests neutral grounding reactor was in operation.)

6) Finally it is worth mentioning that one of the authors of ref. (3) (G. Bán) has made short circuit field tests in Hungary with an existing EHV (750 kV) overhead line, to investigate secondary arc extinguishing times. During said tests the shunt reactors at both ends of the line were equipped with neutral

reactors. The following values were obtained: the mean arcing time was 0.19 sec, and the standard deviation 0.09 sec.

Now on ground of the test results exposed above we can attempt to establish "probability of transient stability" values for the EHV power transmission cases discussed previously. It will be assumed that "adaptive single-pole reclosing" device is applied, which can observe reliably the extinguishing of the secondary arc and initiate immediate reclosing. The probability values below are based on the arcing time measurement results reported above, (we restrict ourselves to cases, when no neutral reactance was applied, because that would presuppose the use of shunt reactors which, in turn reduce stability in advance.)

A.) If the line-length is 500 km (or less), and the power distribution between the EHV line and the lower voltage shunt networks is 2 : 1, then the probability of transient stability ($p_{tr.st}$) in function of the pretransient line-loading (P_{pre}) is as follows:

1) $P_{pre} < 1750$ MW: $p_{tr.st} \cong 1$ (independently of single-pole reclosing dead-time)
2) $P_{pre} < 1850$: $p_{tr.st} \cong 1$ (if the secondary arc-current is not more, than: 60 A)
3) $P_{pre} < 2050$ MW: $p_{tr.st} = 0$ (based on AEP results)
$p_{tr.st} = 0.25$ (BPA results)
$p_{tr.st} = 0.82$ (TVA results)
$p_{tr.st} = 0.841$ (CIGRE results)
4) $P_{pre} < 2200$ MW (surge impedance load) $p_{tr.st} = 0.125$ (BPA results)
$p_{tr.st} = 0.65$ (CIGRE results)
5) $P_{pre} < 2400$ MW: $p_{tr.st} = 0.16$ (CIGRE and soviet results)

B.) If the EHV line-length is 800 km and the power distribution is the same as in case A:

1) $P_{pre} < 1250$ MW: $p_{tr.st} \cong 1$ (uniformly)
2) $P_{pre} < 1300$ MW: $p_{tr.st} \cong 1$ (if the sec. current is not more, than 60 A)
3) $P_{pre} < 1450$ MW: $p_{tr.st} = 0$ (AEP results)
$p_{tr.st} = 0.625$ (BPA results)
$p_{tr.st} = 0.9$ (CIGRE results)
4) $P_{pre} < 1600$ MW: $p_{tr.st} = 0.125$ (BPA results)
$p_{tr.st} = 0.8$ (CIGRE results)
5) $P_{pre} < 1800$ MW: $p_{tr.st} = 0.14$ (CIGRE results)
6) $P_{pre} < 1900$ MW: $p_{tr.st} = 0$

Conclusions

If we regard the transient stability probability values listed above the advantages of applying adaptive single-pole reclosing technique in EHV power transmissions become remarkable. Let us consider her only the CIGRÉ test results, as the number of experiments published there (44 in total) is sufficiently great that probabilistic conclusions of satisfactory confidence level can be drawn.

For EHV/UHV lines not longer, than 500 km and up to pretransient load values of about 80% of the characteristic power, the length of reclosing dead times does not play any role regarding transient stability. Above this limit, however permissible dead times decrease rapidly, and from 85% pretransient load upward the classic reclosing schemes are not sufficient any more to maintain synchronism in case of monophase short circuits.

In the meantime with adaptive technique the probability of transient stability is still around 85% for loads being 93% of surge impedance power. Even with 100% load levels the chances of preserving synchronism are still 65%.

With line length in the range of 800 km the differences are still more stirking: if the pretransient load is above 60%, the classic single-pole reclosing does not work any more, as far as stability is concerned. Adaptive reclosing scheme, however yields about 75% chance of maintaining synchronous operation at load levels of about 74% of the characteristic power.

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