



PS4 – S5-04



Worldwide Survey Results of Questionnaire on Practices Pertaining to Protection, Control, and Monitoring of Series Compensated and Adjacent Lines

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1 INTRODUCTION

In 1950 the first high voltage series capacitors were introduced by Swedish State Power Board (SE) and by Bonneville Power Administration (USA). Both installations were introduced on 220kV transmission systems. Today we can find series capacitors worldwide even at 765kV level.

The main purpose of series compensation in power system is virtual reduction of line reactance in order to enhance the power system stability and increase loadability of transmission corridors. The principle is based on compensation of distributed line reactance by insertion of series capacitor (SC). The generated reactive power provided by the capacitor is proportional to the square of the current flowing through the compensated line and series capacitor. The response of SCs to system loading is this way automatic and instantaneous as long as the capacitor current remains within the specified operating limits.

CIGRE Study Committee B5 (Protection and Automation) created working group WG B5.10 in 2002. The scope of work specified was: "Review the presently available integrated techniques for protecting, controlling and monitoring high voltage lines with series capacitors (including thyristor controlled series capacitors) and the capacitor banks used in those lines and provide recommendations for their applications as well."

As part of its work the WG prepared and issued an international questionnaire on protection, control and monitoring of series compensated networks. The complete subject was divided in following parts: a) General questions, b) Refurbishment of older series compensated installations, c) Specific details on protection of series compensated installations, and d) Specific questions on protection of series compensated and adjacent lines with special emphasis on distance protection, unit protection and protection of multi circuit lines.

The objective of the survey was to get some details of the following:

- ✓ Existing SC lines, installations, trends in the future and issues confronting the technology.
- ✓ Reasons for refurbishment and trends
- ✓ Control and protection equipment used in SC lines and capacitors
- ✓ Special issues concerning distance protections which are predominantly used as line protection

The Working Group received responses from 12 participants from 12 countries as follows: Brazil (BR - CHESF), Canada (CA - Manitoba Hydro), Colombia (CO - Interconexion Electricia S.A. ESP-ISA), France (FR – RTE), Greece (GR - Public Power Corporation), Korea (KR - Korea electric Power Research Institute), Norway (NO - Statnett SF), India (IN - Power Grid Corporation of India

Ltd), Saudi Arabia (GS - Saudi Electricity Company), Sweden (SE - Svenska Kraftnat), South Africa (ZA - ESKOM Transmission) and USA (US - Pacific Gas and Electric Co).

Some highlights of the findings from the survey are described below.

2 HIGHLIGHTS OF SUVEY RESULTS

2.1 Existing SC lines, installations, trends in the future and issues confronting the technology.

Series compensation is used only in few of the countries. The reasons for its usage are:

- ✓ To avoid voltage collapse and to improve quality of supply
- ✓ To increase stability limits
- ✓ To optimize load distribution
- ✓ To transmit more power

In some countries that considered Series Compensation, fears of sub-synchronous resonance were a deterrent. Out of the countries that use SC only a few foresee more lines being equipped with SC in future.

TCSC is used in very few countries. The reasons for its usage are:

- ✓ Power Oscillation detection
- ✓ Sub-synchronous resonance
- ✓ Load flow control

Use of MOVs across SC is a norm. Older installations that were using spark gaps are either replaced with MOVs or are in the process of being replaced.

In some of the countries non-conventional CTs and VTs are used in series capacitor banks.

Directional discrimination of distance relays both in the protected line and in adjacent lines is one of the main issues with regard to line protection. Project specific testing using either EMTP files or real time simulators is done by all the utilities before going in for SC installations to find out adjacent line protections that need to be replaced. While modeling the network for this purpose most countries use only a part of the network.

Current inversion is also one of the problems foreseen by some utilities. Few of them plan to take care of it by selecting suitable protection whereas one utility has reported that in a particular case, this was a reason for not taking up SC installation to avoid costs involved in replacing the protections in adjacent lines.

2.2 Reasons for refurbishment and trends

Countries that are using SC for a long time are either refurbishing or have plans for refurbishment of HV equipment and secondary equipment. The main reasons for refurbishment are:

- ✓ New technology
- ✓ Obsolescence, difficulty in getting spare parts
- ✓ Environmental concerns with respect to old capacitors containing PCBs

2.3 Control and protection equipment used in SC lines and capacitors

- ✓ Use of duplicated line protection is common. Distance/ Distance and Distance/ Directional comparison protection are the normal combinations used. One country has reported use of Distance / Line differential protection. Most countries now use numerical line protections except for few who still are continuing with static type of line protections.
- ✓ In most cases directional or non directional IDMT earth fault relay based on residual current is used for high resistive faults. Use of negative sequence current based directional earth fault relay is also reported by one country. Control/ Monitoring equipment used for lines and banks use both discreet devices and in recent times digital integrated devices.
- ✓ Bank protection is duplicated in most cases although single protection exists too (mostly in older installations).
- ✓ In most countries bank protection is mounted on the ground. Mounting of these on capacitor bank is also reported by one country.
- ✓ Bypassing of capacitor bank is done mostly on a three phase basis. In some cases it is also done on a single phase basis.

2.4 Special issues concerning distance protection which are predominantly used as line protection

- ✓ Zone 1 is set usually at 80% of difference between line and capacitor impedance. Some set even lower. Some do not use Zone 1 at all.
- ✓ Zone 2 is set to 120 % of uncompensated line impedance by most countries. In some countries it is set up to 150% of uncompensated line impedance.
- ✓ Phase locked voltage memory is used to cope with the voltage inversion. Some countries use an intentional time delay to overcome directionality problems related to voltage inversion.
- ✓ Most of the countries carry out real time system studies or EMTP generated files to find out the impact on protections provided in series compensated and adjacent lines. Often these studies reveal that some of the protections on the adjacent lines need to be replaced.
- ✓ MOVs have impact on settings. Increased resistive reach is required. One country has reported that since protection operates before MOV conducts, extra reach is not required.
- ✓ Residual current compensation from parallel lines is not used for distance protection by any of the countries.
- ✓ Gap flashover is expected for faults in the protected series compensated line even for faults with resistance ranging from 4-50 ohms.
- ✓ Due to unsymmetrical gap flashover no major problems have been faced by any country. One country has stated that the settings had to be revised due to this.
- ✓ One country has reported problems due to sub harmonic oscillations, which was addressed by reducing zone 1 setting and in some places disabling it completely.
- ✓ Only one country has reported problems due to high frequency transients that were overcome by providing negative sequence current supervision. All others have not reported any problems related to high frequency transients.
- ✓ Use of phase comparison relay is not common except in US. These are of static segregated type which they plan to replace.

The present paper gives details of survey results of questionnaire pertaining only to sections

- ✓ General on series compensation in power systems and
- ✓ Protection control and monitoring of series compensated and adjacent power lines.

For full details of the survey results the reader may refer the final report of CIGRE: B5-10.

3 SUMMARY OF RESPONSES TO QUESTIONS ON: GENERAL ON SERIES COMPENSATION

The objective of the questionnaire under this section is to give an idea of the existing installations of series compensated lines, both fixed and thyristor controlled types, the likely trends in the future and the issues confronting this technology.

For background material for the questions listed below the chapter “General on series compensation in power systems” in the cigre report WG B5:10 may be referred. The summary of responses received to various questions is given below.

Q: Do you use series capacitors in your power system? If no, are you planning to introduce series compensation in future?

BR, CA, CO, IN, NO, GS, SE, ZA, US use series capacitors. FR and GR do not have them at present and there are no plans to introduce them in the near future. KR does not use series capacitor, but has installed UPFC.

Q: If series capacitors are used in the power system what are the reasons?

The reasons vary from country to country; see Table 1 below.

Table 1: Reasons for using series compensation in different countries

	BR	CA	CO	IN	NO	GS	SE	ZA	US
To avoid voltage collapse				X			X	X	X
To increase transient stability			X	X		X	X	X	X

	BR	CA	CO	IN	NO	GS	SE	ZA	US
To optimize load distribution			X	X	X		X		
To improve quality of supply	X							X	X
To increase power transfer capability						X		X	X

Q: Are there any reasons that deter the use of series compensation?

FR does not require it considering present needs of the network. If in future increased power transfer capacity is required then construction of new lines or upgrade of existing lines is the preferred solution. KR uses UPFC for power flow control. In ZA at times sub-synchronous resonance has deterred the use of series compensation. In NO both sub-synchronous resonance and protection issues deter the use of series compensation.

Q: Do you see more lines being equipped with series capacitors?

BR, CA, CO does not foresee any new lines being equipped with Series Capacitors.

IN, NO, GS, SE and ZA foresee more lines being equipped with Series Capacitors.

Q: Do you use series compensation in shorter lines in order to improve the load distribution?

Only NO uses series compensation in shorter lines to improve load distribution.

Q: Do you use thyristor controlled series compensation (TCSC) in your system? If YES, what are the reasons?

IN, SE, and US use TCSC. The reasons for its usage are as follows:

- ✓ Power oscillation detection: IN, US
- ✓ Sub-synchronous resonance: SE
- ✓ Load flow control: US

In US apart from the reasons given above, MOV requirements to withstand high short circuit current values for series capacitor installations is another reason.

Q: Do you use non-conventional CTs and VTs on series capacitor banks?

IN, GS, SE use non-conventional CTs and VTs on series capacitor banks. BR, CA, CO, NO and ZA have not used them so far.

Q: Did you change your plan to install series capacitors in the past due to some reasons and choose another alternative?

In one particular case ZA has changed plans to install series capacitor due to too high costs involved in replacing adjacent line protections.

Q: If spark gap technology is used is there any plan to change over to metal oxide varistor (MOV) or a combination of spark gap and MOV?

BR, CA, CO, NO, GS, SE have been using MOV or combination of spark gap and MOV from the beginning. In IN on all 400 kV lines this is being used from the beginning. ZA has used spark gap technology but is replacing them with MOV when refurbishment is taken up.

Q: Have you experienced any problems with the protection of series compensated lines? If YES, what are the main issues detected?

BR, CO, IN, NO, GS have replied that they have not experienced any problems. CA, SE have faced cases of false operation, IN has faced problems related to directional discrimination and in ZA low success rate of auto reclosing is one of the problems faced by them. US have experienced problems of directional discrimination, current inversion and false operation.

Q: Do you conduct project specific testing on line protection equipment? If YES, who executes it?

All the countries that are using series capacitors conduct project specific testing on line protection equipment. The details of the agency that carries out the testing are given in **Table 2** below.

Table 2: Project specific testing

	BR	CA	CO	IN	NO	GS	SE	ZA	US
Independent laboratory				X			X		

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Utility representative	X							X	X
Equipment manufacturer	X	X	X	X		X		X	
Independent consultant									
Others		*)	*)	*)	*)				*)

*) Ourselves

Q: If YES, how do you model the system? In a real time simulator or use EMTP or similar generated files for carrying out testing?

SE uses real time simulators. ZA carries out comprehensive testing of the standard relay product on a power system simulator and the tests include series compensated line cases. CO, IN, NO, GS, US use EMTP or similar generated files for off line testing. BR and CA use real time simulator as well as EMTP or similar generated files.

Q: If you are modeling the system, do you model: the whole network, just the series compensated line, part of the network around series compensated line or any other?

All the countries use network modeling for conducting studies. All the countries except US use only a part of the network for modeling. US use the whole network for modeling.

Q: Do you conduct studies to check influence of introducing series capacitor on the behavior of existing protection in adjacent lines?

All the countries that are using series capacitors conduct studies to check influence of introducing series capacitor on the behavior of existing protections in adjacent lines. US also perform open and closed loop tests on adjacent lines for series capacitor installations that have the capacitor placed at the line end and lines that are heavily compensated.

Q: Do you foresee any cases of current inversions in your system particularly when expansion in the system takes place? If YES, what precautions you have taken to take care of the phenomenon?

SE and GS foresee cases of current inversions in their system when expansion in the system takes place. They plan to take care of it by selecting suitable protection. ZA foresees cases of current inversion when system expansion is taken up. And this is the reason series compensation is not pursued in a particular case due to large costs associated with having to replace adjacent line protection equipment. US too anticipate this due to unforeseen expansion or system changes and plan to take care of it by selection of suitable protection. BR, CA, CO and NO do not foresee cases of current inversions in their system.

Q: What is the operating principle of primary (Main 1) line protection and the technology used for it?

Detail of Main1 protection used in various countries is presented in **Table 3** below.

NM...numerical ST...static EM...electromechanical

In CA unblock communication scheme over power line carrier supplemented with a direct transfer trip over PLC system is used.

Table 3: Primary line protection used

	BR	CA	CO	IN	NO	GS	SE	ZA	US
Distance protection	X	X	X	X	X	X	X	X	X
Phase comparison protection									
Line current differential protection						X			
Directional comparison protection					X				
Technology used	NM	NM	NM	NM	ST	NM	EM	NM	NM

Q: What is the operating principle of secondary (Main 2) line protection and the technology used.

Details of Main 2 protection used in various countries are given in **Table 4** below.

Table 4: Secondary line protection used

	BR	CA	CO	IN	NO	GS	SE	ZA	US
Distance protection	X			X	X	X		X	
Phase comparison protection									
Line current differential protection						X			
Directional comparison protection		X	X		X		X		X
Technology used	NM	NM	NM	NM	ST	NM	ST	NM	NM

NM...numerical

ST...static

EM...electromechanical

In CA overreach transfer trip over microwave channel supplemented with a direct transfer trip over microwave is used.

Q: Do you also use a separate earth fault function together with the main line protection to detect high resistance faults? If YES, what kind of scheme do you use? What is the operating principle based on (residual or negative sequence current)?

Details of the earth fault protection used for detection of high resistive faults are presented in Table 5 below.

Table 5: Earth fault protection used for detection of high resistive faults

	BR	CA	CO	IN	NO	GS	SE	ZA	US
Separate earth fault protection used	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Non-directional O/C unit with IDMT delay					X		X	X	
Directional O/C unit with IDMT delay	X		X	X					
Directional comparison									X

In all the countries that use directional or non directional O/C relays, they are based on residual current principle. US have stated that they use both residual current and negative sequence current based relays.

Q: Does the control and monitoring equipment used for series compensated lines comprise: discreet devices or integrated one using numerical technology?

CA, IN, NO, GS, SE, US use discreet devices. BR, CO, ZA use integrated one using numerical technology.

Q: Do you use different setting groups (adaptive) for line protection to better adjust to system conditions?

CA, IN, NO, GS and ZA do not use different setting groups. BR uses different setting groups to better adjust to system conditions. SE is considering implementing it. US use different setting groups. This also depends on the type of line protection, number of segments, and location of series capacitor viz; at the end of the line or in the middle.

4 SUMMARY OF RESPONSES TO QUESTIONS ON: PROTECTION CONTROL AND MONITORING OF SERIES COMPENSATED AND ADJACENT LINES

The questions under this section are classified in two subsections viz; questions related to distance protection and questions related to unit protection. For background material for the questions listed below the chapter “Protection control and monitoring of series compensated and adjacent lines “ in the CIGRÉ report WG B5:10 may be referred.

Influence of series compensation on performance of line protections based on different operating principles has been addressed within this chapter in detailed way. In this respect distance protection, directional comparison protection principles, phase comparison are presented in detail. Directional comparison protections have been based on superimposed quantities and on the other side directional residual and negative sequence over current protections. Special attention has also been put on series compensated and adjacent line back-up protection philosophies, auto reclosing on series compensated lines and fault location possibilities.

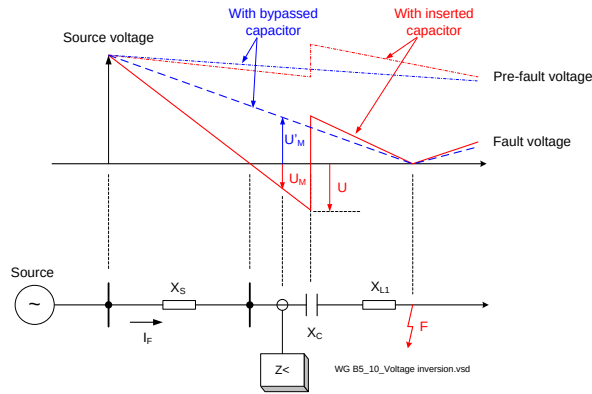


Fig. 1: Voltage inversion on series compensated line

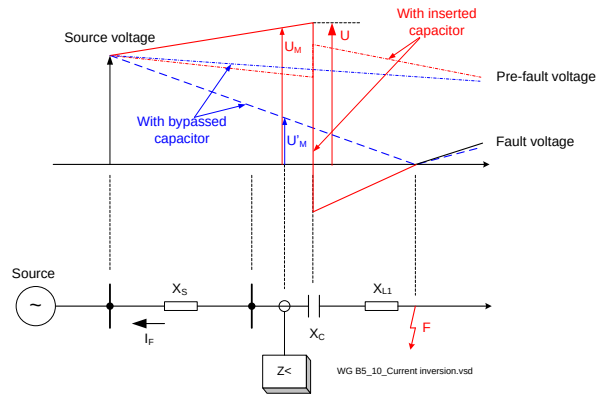


Fig. 2: Current inversion on series compensated line

4.1 Questions related to distance protection

These questions pertain to some specific details when distance protection is used either as the primary or secondary protection.

Q: What is the underreaching (Zone 1) and overreaching (Zone 2) setting used in teleprotection schemes?

Table 6: Distance protection Zone 1 reach settings

	Zone 1 reach [% of line length]	Rationale
BR	0	Overreach problems confirmed by testing with EMTP simulation.
CA	80	Manufacturer recommendation. Confirmed by testing with Comtrade files from EMTP simulation
CO	35	-
IN	80	- All lines are provided with series capacitor at one end - At capacitor end Z1 is set to 80% of line impedance. - At remote end (if single circuit line) Z1 is set to 80% difference between line impedance and capacitor impedance. Additionally a reduction factor for taking care of sub-harmonic oscillations without any time delay is used. - At remote end (if double circuit line) Z1 is set to 80% of line impedance and capacitor impedance. Additionally a reduction factor for taking care of sub-harmonic oscillations with 100ms time delay is used.
NO	80	80% of the difference between the line inductance and the capacitor reactance.
GS	40	Since line differential protection is provided to cover complete line and also POTT is used with Zone 2 which covers the whole line.
SE	85	85% of the difference between the line inductance and the capacitor reactance
ZA	80	80% of the difference between the line inductance and the capacitor reactance (unless there is a need for further reduction to avoid overreaching due to resonance)

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	Zone 1 reach [% of line length]	Rationale
US	50	Lines are heavily compensated with multiple segments at each end of the line

Table 7: Distance protection Zone 2 reach settings

	Zone 2 reach [% of line length]	Rationale
BR	120	120% of uncompensated line impedance is used with POTT
CA	120	The value is typically 100% of the line positive sequence impedance + 50% of positive sequence impedance of the shortest line leaving the remote bus. Else 120% of the line so as to shorten the reach when the capacitors are in service.
CO	120	120% of uncompensated line impedance is used with POTT communication scheme
IN	120	120% of uncompensated line impedance is used with POTT communication scheme
NO	150	Normally 150% of uncompensated line impedance is used with POTT communication scheme. Can vary dependent on short circuit studies.
GS	120	120% of uncompensated line impedance is used with POTT communication scheme.
SE	150	150% of uncompensated line impedance is used with POTT communication scheme
ZA	120	As a percentage of uncompensated line impedance. Minimum 120% and as far as possible considering system limitations such as overreaching of remote end transformers, etc.
US	120	Lines are heavily compensated with multiple segments at each end

Q: What kinds of measurement techniques are used to cope with voltage inversion?

In all the countries phase locked memory is used to cope up with voltage inversion. Saudi Arabia has also informed that they use an intentional time delay.

Q: Have you conducted any system studies to find the impact of series compensation on the performance of protections installed on adjacent lines? If YES, was there any need to change the protection on adjacent lines after the introduction of series compensation? If YES, what criteria were used and how many line ends were affected?

In all the countries system studies are carried out to find the impact of series compensation on the performance of protection installed on adjacent lines. The types of faults considered were: 3ph faults, 2ph to earth faults and 1ph to earth faults. In BR, CA, GS there was no need to change the protection on adjacent lines whereas in CO, IN, NO, SE, ZA and US some protection in the adjacent lines had to be replaced. The number of protection systems replaced varied from 2 to as many as 21 line ends. Some countries also consider fault resistance, minimum/maximum source impedance, and minimum/maximum load flow.

Q: If you use MOVs, what is their impact on the operation / setting of line protection?

IN, CO, NO, SE, US had to increase the resistive reach due the usage of MOVs. GS had to adjust filtering characteristic. In CA, EMTP studies have revealed that the MOV operation do not affect the line protection settings as the line protection decision is taken before the MOV bypass takes effect. ZA has experienced that zero sequence compensation factor had to be reduced by the same percentage as the positive sequence compensation factor to prevent overreaching of Zone 1 for external faults involving ground.

Q: What is your experience with residual current compensation from parallel line?

None of the countries that have parallel lines are using zero sequence current compensation from parallel lines.

Q: When do you expect flashover of spark gaps?

The responses here vary. Some have indicated that this is expected for faults in the protected line for fault resistance values ranging from 4 Ohms to 50 Ohms. Some countries have stated that it relates to continuous voltage of the capacitor rather than the fault impedance.

Q: Does unsymmetrical flashover of the gaps occur in your power system? If YES, what problems have been experienced and what countermeasures have been taken?

NO, SE, ZA and US have reports of unsymmetrical flashover of the gaps occurring in their system. While NO and ZA has not faced any problems so far, SE has faced false operation of protective relays which has led to revision of settings. BR, CO and GS have replied that they have not experienced it.

Q: Have you experienced any under/overreach problems at sub-harmonic oscillations? If YES, how did you address the problem?

None of the countries except ZA have experienced any such problems. ZA faced some problems and this was addressed by reducing zone 1 setting and in some places disabling zone 1 completely.

Q: Have you experienced any security problems with high frequency transients caused by flash over of spark gaps or line energisation? If YES, how did you address the problem?

No country except CA has experienced any such problems. CA experienced that the Main 2 protection was too sensitive to SC switching. This was overcome by providing negative sequence supervision.

4.2 Questions related to unit protection

These questions pertain to if older generation of unit protections like phase comparison relays are used either as the primary or secondary protection for the series compensated lines.

Q: Do you have older generation of phase comparison relays? If YES, do you plan to replace them in near future and if so what is the reason for their replacement? What will be the operating principle of the replacing protection scheme?

None of the countries except US have any older generation of phase comparison relays based either on the segregated principle or on non-segregated principle. US has used static type segregated phase comparison relays. They plan to replace them in near future due to obsolescence, performance problems and lack of spares. They plan to replace them with numerical segregated phase comparison relay and directional comparison protection.

4.3 Questions related to protection of multi-circuit lines

These questions are to find out the experience, when series capacitors are used in double or multi-circuit lines. Here mutual impedance plays an important role. The capacitor will reduce the self-impedance while the mutual impedance will be the same as is without series capacitors. This means that the effect of the mutual impedance will be much higher than on power lines without series capacitors.

Q: Have you experienced protection problems in such cases? If YES, can you describe the problems? Do you think unit protection is the best for such lines?

Out of all the respondent countries only SE has faced fault current reversal problems in such cases. In their opinion unit protection is the best to overcome this. US have faced problems and they too feel unit protection is best in such cases.

5 CONCLUDING REMARKS

Recognizing the utility of series compensation in World Context, many more series compensated installations are planned at selected transmission corridors with the following objectives:

- ✓ Enhance the transmission capacity of the existing transmission lines where constraints are being faced in evacuation of power, at minimum investment and time
- ✓ To plan high capacity lines with series capacitors in the new corridors where more generating projects in future are expected to come.
- ✓ To optimize load distribution between different parts of high voltage networks

- ✓ To increase power system stability limits
- ✓ To avoid voltage collapse and to improve quality of supply
- ✓ To better control power system oscillations (TCSC)
- ✓ To prevent subsynchronous resonance (TCSC)
- ✓ To better control system load flow (TCSC)

Latest trends in protection of series compensated and adjacent power lines show increased use of current differential protection. Even more, implementation of modern IEDs with integrated current differential and distance protection functionality as Main 1 and Main 2 protection system is becoming nearly a standard. Distance protection serves in this respect many times only as back-up function to current differential protection in case of its communication link failure. It is self understanding that they use different communication paths if not even different communication principles, e.g. digital communication systems and power line carrier.

Also one more unwritten ground rule on series compensation is most probably going to be exchanged in near future. Introduction of renewable resources like big wind farms and solar fields far from existing conventional generating areas will considerably change standard flows of electric power in existing EHV networks. This will require between others also introduction of series compensation even on short EHV lines, e.g. less than 50 km long 400 kV lines □ [2].

Introduction of series compensation (fixed and / or thyristor controlled) in EHV power lines leads to non-linear performance of a complete installation during power system faults and causes this way specific conditions for operation of different protection functions applied. It is practically impossible to provide for these functions simple setting instructions as for the cases in non-compensated networks. Power utilities, protection producers and different other institutions perform for this reason thorough system simulation studies either by use of real time simulation facilities either by use of transient simulation software replaying the results (time dependent relay point currents and voltages) directly to proposed protection devices. This way they:

- ✓ Have an opportunity to check whether the proposed devices have built-in additional functionality required for protection used in series compensated networks. Such tests are usually performed as additional specific type tests on specially selected network models and with predefined test conditions and expected results.
- ✓ Have a possibility to fine tune protection configurations and settings to specific conditions (e.g. voltage and current inversion, increased apparent resistance due to MOVs, etc.) for a specific installation (project specific tests). Sometimes even some changes in already established standard solutions are necessary.

Worldwide practical experiences have shown that such approach leads to reliable operation of protection systems in series compensated networks.

The CIGRE B5: WG-10 report in general and the above survey results in particular should help the protection engineers in fine tuning the practices currently adopted.

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