Assessment of measures to improve cost-effectiveness, reliability and TRV risk management in Finnish series compensated system

Olli-Pekka Janhunen, Kimmo Nepola, Tuomas Rauhala

Abstract— **Between years 1997 and 2016 eleven fixed series capacitors (FSCs) have been built to enhance the interarea transmission capability of Finnish 400 kV transmission system. During these years, Fingrid (Finnish transmission system operator) has experienced various reliability issues with the existing FSCs. In early 2017 Fingrid launched a development project with target to improve the reliability and cost-effectiveness of Fingrid's FSC fleet by developing the FSC specification, project and maintenance practices. As a part of the project, possibilities to develop FSC overvoltage protection requirements were studied for more robust, reliable and cost-effective technical solution. To compare investment costs and risks of FSC protection with and without forced triggered spark gap, an extensive EMT study was carried out. The study consisted of MOV energy and TRV-risk assessments including extensive sensitivity analysis covering 11 existing and 2 new FSC installations. Based on results of the study, new improved MOV dimensioning principles and the line circuit breakers' TRV requirements were established to address for future FSC investments and refurbishments.**

Keywords: **fixed series capacitors, FSC, MOV dimensioning, gapless series capacitor, series compensation, TRV, transient recovery voltage**

I. Introduction

A. *Background*

During period 1997 – 2016 transmission capability between Sweden and Finland and South- and North-Finland have been increased by installation of 11 fixed series capacitors (FSCs) on existing 400 kV transmission lines [1]. By 2025, two new FSCs will be installed in Finnish 400 kV network. In addition to these two greenfield FSCs, the refurbishment of C&P systems of five out of eleven existing FSCs is scheduled for the same period of time. Considering the various reliability issues and life-cycle management issues Fingrid has experienced with existing FSC fleet, Fingrid launched a three-stage development project in early 2017 with the target to develop the FSC specification, implementation, project and maintenance practices for the coming investment and refurbishment projects. One of these stages, covered in this paper, focused on improving the reliability and the cost-effectiveness of future FSC installations by assessing a possibility to implement FSC overvoltage protection without a forced triggered spark gap (SPG).

Spark gaps are applied in FSC installations to ensure a fast bypass of FSC during a grid fault. The fast bypass reduces accumulated MOV energy in internal faults and transient recovery voltage (TRV) risk of line circuit breakers. As the MOVs are one of the main cost components in the FSC investment, the SPG or similar fast protective device (FPD) has been a requirement also in Fingrid's FSC specification. However, due to some life-cycle management related benefits and the challenges experienced with the reliability of existing SPGs and FPDs, a gapless overvoltage protection appears as an attractive option for future FSC installations. This was considered to require, however, fundamental review of FSC design requirements, because typical TRV or MOV analysis provide results and recommendations based on the worst case scenario based on multiple unfavorable conditions which are present at the same time. The combined probability for this worst case scenario to realize is often very limited and the impact of this combination on FSC cost is highlighted especially in case of gapless FSC. When decisions are made based on the worst case scenario which reflects extremely rare combination and sequence of events, it is possible that the cost-effectiveness of the solution is far from optimal. To avoid over-dimensioning of the grid components, the decisions shall take both the probability and consequences of the each scenario into account. In this work, these approaches has been brought to MOV and TRV analysis to allow cost-benefit and risk assessment of different MOV dimensioning requirements. To establish extensive set of results for such assessment, EMT study consisting of two main tasks was performed: 1) assessment of different MOV dimensioning criteria and factor, and 2) TRV risk assessment and management.

This paper presents the background, the study approach and the key conclusions of the extensive study with target to analyze the cost-effectiveness and related TRV risks of different requirements related to overvoltage protection approach of the FSC. Chapter II presents different aspects related to implementation of overvoltage protection for gapless FSC. Chapter III covers the factors that were taken into account in the study in order to ensure that various aspects including their probability is taken into account in the simulations. Chapter IV provides examples how the results of the study were processed and presented in order to provide solid basis for cost-benefit and risk assessment. Chapter V provides summary of the main conclusions and recommendations of the work.

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II. GAPLESS OVERVOLTAGE PROTECTION IMPLEMENTATION

A. *Aspects related to cost-effectiveness of gapless FSC*

The basic structure of the FSC is presented in Figure 1. As presented in Figure 1A, the gapless FSC model contains, in addition to capacitors, MOVs, damping inductor, damping resistor and bypass switch. In addition to described components, traditional FSC model, presented in Figure 1B, contains forced triggered spark gap or fast protective device.

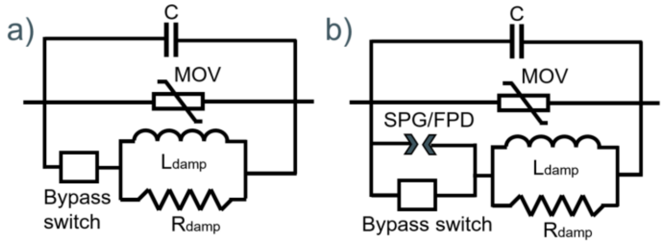

Figure 1 Simplified structure of the FSC a) without and b) with SPG

In FSC installations, the cost-effectiveness of a gapless FSC depends on extra MOV costs caused by a longer bypass time of gapless FSC and on savings in SPG components. Thus, in order to assess cost-effectiveness of the gapless FSC, the MOV calculations need to be carried out with and without SPG.

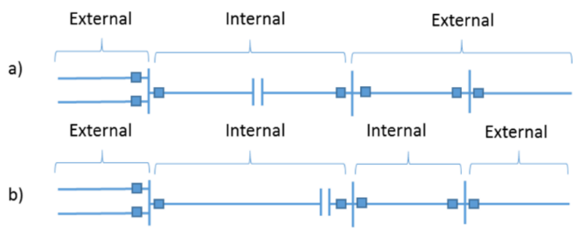

Figure 2 Example of external and internal fault areas, when the FSC is located at a) middle of a transmission line, b) end of a transmission line

The MOVs are typically designed to withstand worst external fault (see Figure 2) without a need for FSC bypass. In addition, the MOV energy capability shall be sufficient to allow re-insertion of FSC after a first internal fault. In order to mitigate the risk of MOV destruction due to multiple severe faults, the MOV energy capability shall always be adequate to absorb the energy accumulating in a second internal fault. Thus, MOV dimensioning can be made by choosing greater of the following worst-case energies:

1) Sum of external and second internal fault energies
2) Sum of first and second internal fault energies.

In an external fault, the fault time depends on line protection delay and in a first internal fault, the fault time experienced by FSC depends on FSC protection delay and operation delay of SPG (1–2 ms) or bypass switch (20–50 ms). In a second internal fault, the bypass signal is assumed to be sent immediately by FSC energy protection to SPG and bypass switch. Since the bypass is significantly slower with a bypass switch than with SPG, the MOV costs are higher for FSC without than with SPG. In a greenfield FSC, a part of the increased MOV costs can be funded with the price of SPG components. In this study, the average price of the SPG components was estimated based on Fingrid's previous FSC projects.

B. *TRV-risk and risk management*

In addition to MOV energy, the increased bypass delay of FSC has an impact on line circuit breakers' TRV-risk. TRV is known to be the decisive parameter that limits interrupting capability of a high voltage circuit breaker. International standard IEC-62271-100 [2] specifies the TRV withstand of a circuit breaker, which manufacturer must verify in different test duties.

A series capacitor is known to increase the TRV of a circuit breaker due to trapped charge on a capacitor, and thus, TRV peaks in series compensated lines, especially with high compensation degree and protective voltage, may exceed the requirements of IEC-62271-100 if the capacitor cannot be bypassed before the first line circuit breaker pole clears [3-6]. For example, an extensive TRV study [3] proposes 1120 kV TRV peak and 1.0 kV/us RRRV standardization requirements for 420 kV series compensated lines. Since the requirements are out of reach of IEC-62271-100, a TRV risk management method is required. Based on [3-6], the following TRV risk mitigation methods could be applied in series compensated lines:

1) Ensuring fast bypass of the FSC
2) Paralleling MOV with the circuit breakers
3) Dividing FSC into multiple parts
4) Adding extra TRV test requirements for circuit breakers
5) Reducing protective voltage of the FSC

Typically, as mentioned earlier, in series compensated network TRV mitigation is applied with FSC fast bypass executed by SPG or FPD. However, the operation of a traditional forced triggered spark gap is generally limited by minimum SPG flashover voltage, which depends on short-circuit current flowing through FSC. Due to required minimum short-circuit current of the SPG to trigger, TRV risk cannot be mitigated in all remote end faults. With a gapless FSC, the bypass is delayed significantly, which increases the amount of fault cases where the FSC cannot be bypassed before the line circuit breaker's first pole clears. In this paper, as an alternative TRV mitigation method, the impact of reducing protective level of the FSC is studied, and extra TRV test requirements are specified for the line circuit breakers located in series compensated lines.

C. *MOV dimensioning requirements*

In a typical FSC specification, the MOVs are required to be able to withstand any external fault (dimensioning fault) with maximum fault clearing time without bypassing the FSC and additionally the time required to bypass the FSC in case of any internal or external fault occurring when varistors are still fully loaded due to the dimensioning fault. The failed autoreclosures and N-1 operational contingencies are thus not required to be taken into account on MOV dimensioning. The calculations are often made with simulation model representing certain, e.g. the maximum short-circuit-current representing grid operation scenario where most of the generators are connected to the grid.

Based on the discussion, the following study subjects were identified related to MOV dimensioning requirements:

1) What is representative maximum fault clearing time?
2) Should the failed autoreclosure cycles be considered?
3) Should N-1 contingencies be considered?
4) What is representative short-circuit current level?

III. STUDY METHODS

A. *Modeling*

Grid model: The EMT study presented in this paper was conducted using model containing northern part of Finnish 400 kV transmission lines and some parts of 220 kV and 110 kV transmission lines. Some 400 kV transmission lines located in Sweden were also included in the study. Transmission lines were modeled with frequency dependent models.

Fixed Series Capacitor: Simplified structure of a FSC is presented in Figure 1. The used FSC bypass method is presented for MOV assessment in section III.B.1 and for TRV assessment in chapter III.C.2.

Circuit breakers: A line circuit breaker was modeled as an ideal switch, which opens in the first current zero crossing after the specified open delay without taking into account the arc characteristics.

Metal-Oxide-Varistors: The MOVs have been modelled based on UI-curve representing nonlinear behavior of the MOVs. The UI-curve of each FSC was provided by the FSC manufacturer as a part of the project documentary.

B. *MOV Simulations*

1) Internal fault energy

In order to assess cost-effectiveness of gapless FSC, the EMT simulations were carried out to all existing eleven FSCs and two new FSCs by choosing 22 fault locations in the meshed Finnish series compensated power system. The locations were selected in a way that all FSC terminal faults were able to be simulated. The simulations were carried out with two different bypass switch operation delays, five point of waves and four fault types.

In the calculations, the bypass delay of 23.5 ms and 43.5 ms (including 2.5 ms FSC protection pick-up delay) were chosen to represent operation delay of fast and slow bypass switches. For FSC with the SPG, the accumulated energy was calculated by multiplying the highest simulated energy rate of rise with operational delay (1.5 ms) of the SPG, and for the gapless FSC the simulated accumulated energy of MOVs was used. In the simulations focusing on accumulated MOV energy in first internal fault, FSC protection was modeled in order to take FSC current protection delay (extra delay of 10-15 ms) into account.

2) External fault time and energy

Sufficient external fault time for MOV calculations can be found by estimating a distribution of line protection delay in Finnish 400 kV grid. The best estimation would be found by using real fault clearing times from disturbance fault recorders. However, since this information was not in easily usable form, in this study the fault clearing time was estimated based on operation delays of an each component.

In the Finnish 400 kV grid, the fault clearing time can be assumed to consist of protection relay operation delay, telecommunication delay between the relays and the line circuit breaker operation delay. Based on available measured operation delays and Fingrid device specialist interviews, the delays were modeled with normal and gamma distributions. The sum of distributions were assumed to represent the distribution of fault clearing time. Since, the operation time of line circuit breaker was found to be dependent on the circuit breaker type, the sum distributions were calculated with three different line circuit breaker operation distributions. Based on Figure 3, 70 ms fault clearing time can be assumed to represent about 99 % of the cumulative fault clearing time in Finnish 400 kV grid.

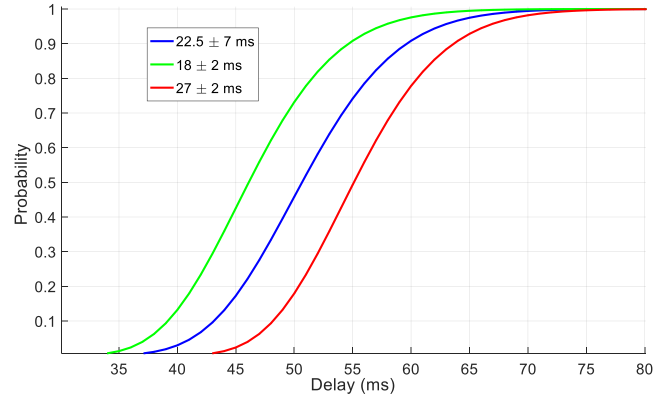

Figure 3 Distribution of estimated cumulative fault time in Finnish 400 kV power grid with three different line circuit breaker open time.

An EMT-study was carried out in order to study the MOV price difference between the Fingrid's existing 100 ms and the alternative 70 ms fault clearing time requirement. Fault locations were placed in each substation, limiting internal fault area, in order to find the highest accumulated energy in external fault.

3) Failed autoreclosures

The price of taking the failed autoreclosures account on MOV dimensioning was estimated by simulating the energy caused by a failed autoreclosure. On the other hand, the risk of FSC unintentional bypass caused by failed autoreclosure was assessed based on simulations and estimated probability of each fault type. Based on results, a suggestion for if failed autoreclosures should be considered in MOV dimensioning was given.

4) N-1 operation contingencies

The impact of N-1 contingencies to MOV costs were assessed by observing MOV energy of one FSC in four different carefully selected N-1 contingencies. The probability of MOV destruction and unintentional bypass of the FSC were assessed based on the simulations, and a suggestion for if N-1 contingencies should be considered on MOV dimensioning was given.

5) Short circuit current level of the grid model

The short-circuit current level impact on MOV energy was simulated by using grid model representing maximum and minimum fault current level of the Finnish grid. The history based data for probability of different fault types to occur during maximum short-circuit current level was used to assess if maximum short circuit current need to be used in MOV dimensioning.

C. *TRV Simulations*

1) Studied transmission lines

In order to estimate TRV-risk with different overvoltage protection schemes, simulations were carried out to one series compensated line, where Uusnivala FSCs are located in the middle of the line, and to one series compensated line, where Kivijärvi FSC is located in 1/3 of the line.

The main difference between the studied transmission lines is a difference between protective level voltages of the FSCs due to high nominal current of the Kivijärvi FSC (Table 1).

Table 1 Information about the studied FSCs

FSC	Compensation degree (%)	Nominal current (A)	Protective level (pu)	Protective voltage (kV)
Kivijärvi	75	2300	2.0/2.3	390/449
Uusnivala	74	1400	2.3	2x123

2) Uncertainty factors

The uncertainty factors impacting TRV results have been taken into account in the simulations in following ways:

- Fault location: 17 fault locations were placed on Petäjäskoski-Pyhänselkä (PE-PS) line and 6 locations on Alajärvi-Pikkarala (AJ-PR) line, see Figure 4.

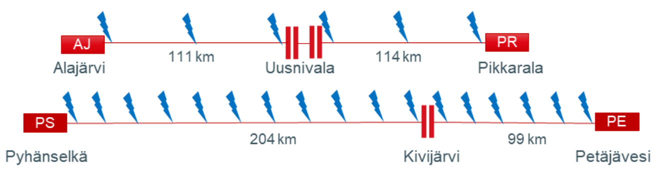

Figure 4 Studied series compensated transmission lines and fault locations

- Fault type: 1-phase-to-ground, 2-phase, 2-phase-to-ground and 3-phase-to-ground faults were included to the study.
- Fault clearing time: Fault clearing time was varied based on estimated normal and gamma distributions of protection relay, telecommunication and line circuit breaker opening delay. Normal distributed random delays ±2 ms were used for each circuit breaker pole to model variation between clearing time of the poles. Sensibility analysis were made with three different opening times of a line circuit breaker.
- Fault inception: 10 different fault inceptions were used on PE-PS line and 20 fault inceptions on AJ-PR line
- FSC bypass time: The bypass signal was sent by FSC line current, MOV energy rate of rise or MOV accumulated energy protective functions. In addition, an external bypass signal from protective relay was modeled. The total FSC bypass delay included either the SPG delay (1.5 ms) or bypass switch delay (23.5 or 43.5 ms).

3) TRV mitigation

TRV-simulations were carried out with two different FSC protective levels. The protective level was varied between 2.3 and 2.0 based on IEC-60143-2 [7] suggestion range. FSC internal protection pick-up settings were recalculated between the simulation scenarios to ensure comparable results.

As another TRV mitigation method, the line circuit breaker with higher 550 kV nominal current was introduced. In the calculation, the simulated curves were compared to IEC-defined 550 kV and 420 kV interpolated [8] envelopes and the amount of envelope violations were compared with both of the FSC protection schemes. However, since TRVs on series compensated lines are typically characterized by high transient recovery voltage peaks and low RRRVs compared to IEC requirements, extra specified TRV test requirements for circuit breakers seemed the most sufficient mitigation method. The suggested TRV requirements were given for the both transmission lines by finding a low risk requirements which, based on circuit breaker manufacturers, might be possible to be fulfilled by some of the 420 kV circuit breakers. Thus, the new TRV requirements are not expected to cause extra costs.

IV. Simulation Results

A. *MOV dimensioning criteria*

The aspects and factors affecting the MOV dimensioning were analyzed based on set of 10000+ simulation results based on combination of parameters described in section III.B. Due to the fact that the output of the study provided results for 13 FSCs from 60 fault locations, one of the key challenges was to present the results in relevant manner to allow the analysis of different factors on MOV dimensioning. Based on various different, rather complex graphs following main conclusions were made.

In the Finnish series compensated network, 70 ms external fault time was found reasonable for MOV dimensioning. By using 70 ms external fault time instead of previously used 100 ms, with gapless FSC average estimated savings on MOV costs are 13 % in Finnish power system.

In a meshed series compensated network, it is not always possible to choose the circuit breaker, which executes the autoreclosure, in a way that the fault current caused by failed autoreclosure does not go through any FSC. Based on the simulations, in Finnish series compensated network estimated average mean time between the unintentional FSC bypasses is once every 325 years per FSC caused by a failed autoreclosure, which was found acceptable risk level. On the other hand, the requirement of considering failed fast autoreclosure on MOV dimensioning would cause a need to increase MOV energy capability by 33 % on average.

In Finnish series compensated network, a requirement of considering N-1 contingencies on MOV dimensioning would cause a significant increase on MOV costs. Based on the simulations N-1 contingencies do not cause a risk for MOV destruction, and a risk for unintentional bypass to cause stability problems in the grid was estimated to be very limited.

During the last 20 years, about 80 % of the faults occurred in Finnish 400 kV grid have occurred in summer months during a low short-circuit current level period. In the simulations, accumulated MOV energies had only small differences between minimum and maximum short circuit current level, and thus the risk for FSC unintentional bypass or MOV destruction was found very limited.

B. *Cost-effectiveness of the gapless FSC*

Cost-effectiveness of the gapless FSC solution was analyzed along with the factors and conditions affecting the design and dimensioning of the overvoltage protections as described in Section II.A and III.B. In the simulations, a topology and short-circuit current level of a nearby grid were found to have a significant impact on cost-effectiveness of the gapless FSC. For illustrative purpose, simulation results of four FSCs with fast and slow bypass switches and with protective gap are presented in Figure 5. In addition, the installed MOV energy capability has been presented for existing FSCs (others than Kivijärvi FSC) for illustrating a possibility to remove SPG in C&P upgrade without causing a need to change the MOVs.

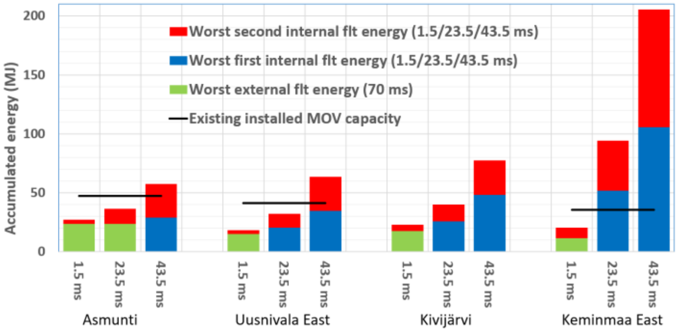

Figure 5 Simulated MOV energies for FSCs with fast (23.5 ms) and slow (43.5 ms) bypass switches and with spark gap (1.5 ms).

Based on the results, the gapless implementation with fast bypass switch is economically reasonable option for most of the greenfield FSCs. When a new FSC is built into the middle of a 400 kV transmission connection, the gapless FSC was found cheaper than FSC with SPG. When the FSC locates at a substation in the end of a transmission line, the cost-effectiveness of the gapless FSC is dependable on the topology and the short-circuit-current of the nearby grid.

In Finnish 400 kV grid, for eleven out of thirteen FSCs, the gapless FSC with fast bypass switch was found cheaper than FSC with SPG. However, the operation delay of the bypass switch (as illustrated in Figure 5) and exact MOV prices have significant impact on cost-effectiveness of the gapless FSC.

C. *TRV risk*

1) *Low protective voltage*

Based on the simulations applied for the series compensated transmission line, gapless FSC increases TRV risk of line circuit breakers. TRV risk was higher with the slow bypass switch than with the fast bypass switch. With the both overvoltage protection types, a faster line circuit breaker operation increased TRV risk experienced by the line circuit breakers.

For illustrative purposes, in Figures 6 and 7 have been presented percentile division of simulated TRVs in LLLG faults in each time step without and with SPG, respectively. In the figures, simulated curves have been divided to different subplots (T10, T30 and T60) based on magnitude of fault current flowing through the phase during an interruption.

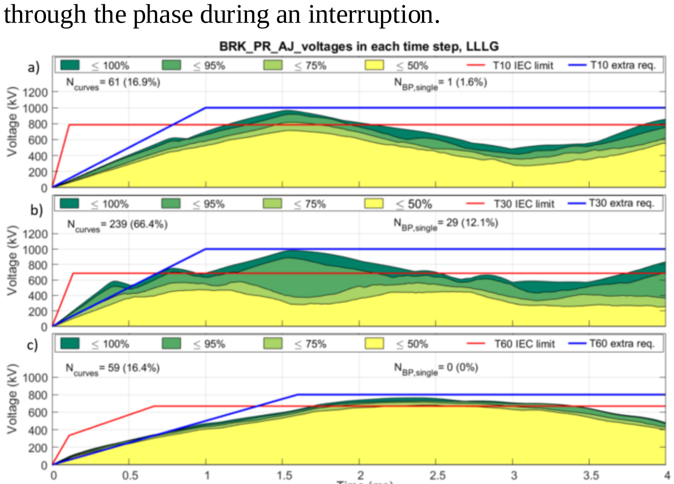

Figure 6 Percentile division of Pikkarala – Alajärvi line breaker (BRK_PR_AJ) simulated TRV for all phases in LLLG faults when Uusnivala FSCs have gapless overvoltage protection. The plots present simulated TRV for different IEC based envelopes a) T10, b) T30, c) T60.

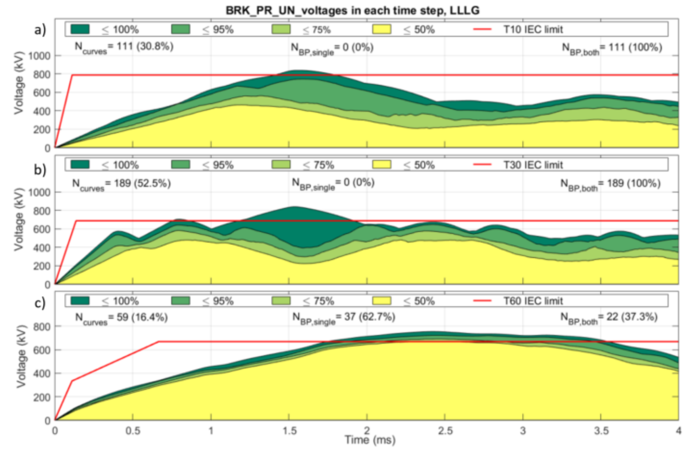

Figure 7 Percentile division of Pikkarala – Alajärvi line breaker (BRK_PR_AJ) simulated TRV for all phases in LLLG faults when the FSCs of Uusnivala FSCs have protective gap. The plots present simulated TRV for different IEC based envelopes a) T10, b) T30, c) T60.

For each test duty, extra TRV envelopes for the circuit breakers located in the transmission line were specified (blue envelope) and presented in Figure 6. As shown in Figure 7, IEC envelope violations (red line) occurred also, when the FSCs were equipped with SPG. However, based on risk assessment, the probability of a significant IEC violation was seen very limited, and thus no extra TRV requirements were not seen necessary.

In the figures, each envelope subplot will include information considering the number of TRV curves (N_{curves}) used in particular subplot and their percentage from total population of the specific subset (i.e. from total number of curves used in the figure). In addition, each subplot defines number of cases ($N_{\text{BP,single}}$) where one of the FSCs at the same phase is bypassed before line breaker has cleared and where both FSCs ($N_{\text{BP,both}}$) at the same phase fulfill the same bypass criteria.

Based on the figures, the fast bypass was executed effectively with the SPG, since in all of the simulation cases at least another FSC fulfilled the bypass criteria. With gapless FSC, the bypass criteria was fulfilled only if a fault was detected by FSC line current or MOV energy rate of rise protection.

2) *High protective voltage*

In the simulations, protective level voltage was pointed out to have a significant impact on TRV if FSC cannot be bypassed before the first line circuit pole opens, and thus reducing the protective level voltage of FSC was found out as an effective TRV mitigation method as presented in Figure 8.

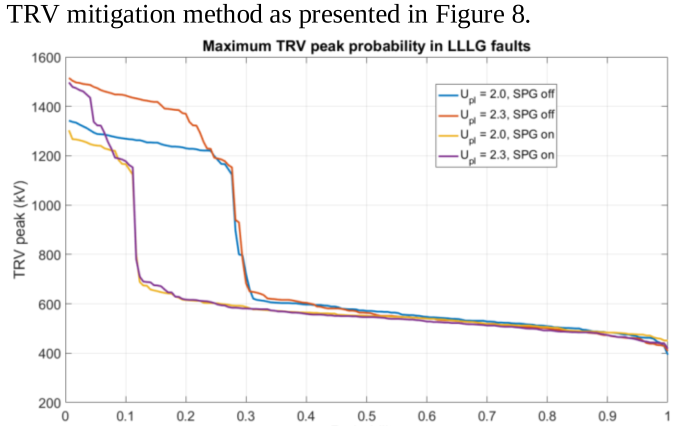

Figure 8 Cumulative probability of Petäjävesi – Pyhänselkä line circuit breaker simulated TRV peak (worst phase) in LLLG faults.

In Figures 9 and 10 have been presented simulated TRV-curves without and with SPG, respectively. As illustrated in the figures by green curves, indicating the phase has fulfilled the bypass criteria, TRV can be effectively mitigated by a fast bypass. However, since minimum flashover voltage of a traditional spark gap limits a possibility to ensure the fast bypass in remote end faults, significant amount of cases did not fulfill the bypass criteria, indicated by a black curve. In these faults significant IEC violations were observed.

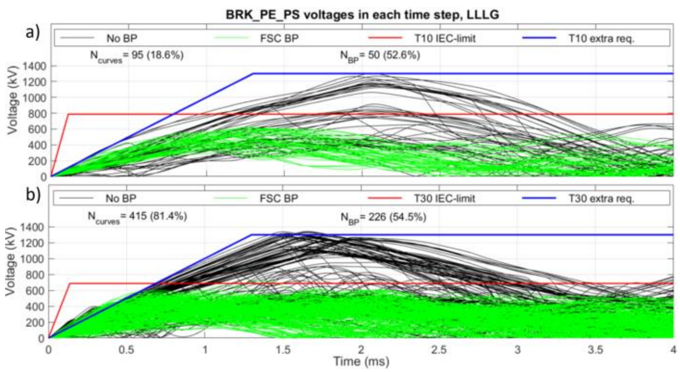

Figure 9 TRV-curves of Petäjävesi - Pyhänselkä line circuit breaker in each simulation time step at LLLG-fault, when the Kivijärvi FSC has gapless overvoltage protection with protective level 2.0. The plots present simulated TRV for different IEC based envelopes a) T10, b) T30.

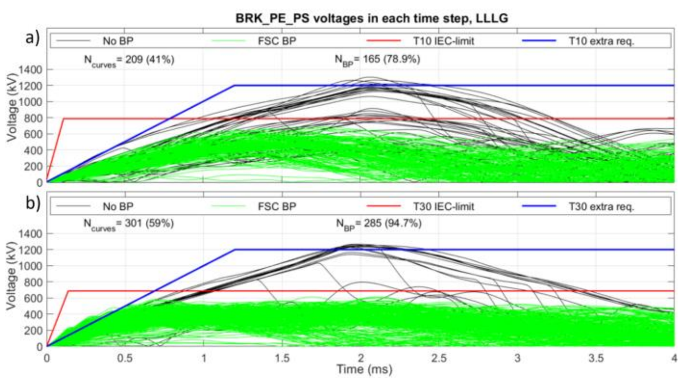

Figure 10 TRV-voltages of Petäjävesi - Pyhänselkä line circuit breaker in each simulation time step at LLLG-fault, when the Kivijärvi FSC with protective level 2.0 is equipped with spark gap. The plots present simulated TRV for different IEC based envelopes a) T10, b) T30.

Based on the made TRV risk assessment, extra TRV requirements were suggested and presented in Figures 9 and 10. Even though the probability of high TRV peak is significantly smaller when the FSC equipped with than without spark gap, the maximum observed TRV peak is approximately equal with both protective schemes. Thus, the traditional spark gap was not found sufficient TRV mitigation method, when a transmission line contains a FSC with high protective voltage.

V. Conclusions

In this paper, ways to improve reliability and cost-effectiveness of FSCs were studied by implementing an extensive EMT study. A new approach is brought in this paper to MOV and TRV assessments by considering probability and consequences of different scenarios when decisions are made based on simulations. The following assessments are suggested to be dealt in order to find out cost-effective low risk MOV dimensioning principles, and thus to avoid over-dimensioning of the MOVs:

1) Specifying maximum external fault time based on delay of line protection with reasonable margin, and estimating MOV energy and costs caused by an external fault. 70 ms fault time was found reasonable option for Finnish power system.
2) Specifying internal fault time based on FSC bypass delay, and estimating accumulated MOV energy and costs caused by an internal fault.
3) Estimating accumulated extra MOV energy caused by failed autoreclosures or N-1 contingencies, and assessing the probability and consequences of unintentional bypass of FSC due to failed autoreclosure or N-1 contingencies. In Finnish power system, the risk caused by N-1 contingencies and failed autoreclosures was found very limited, and thus not required in future FSC specification.
4) Defining reasonable short-circuit current level based on probability of different faults. Based on the study results, the MOV dimensioning can be applied in Finnish power system with grid model representing short-circuit current level of summer period.

After the basic MOV dimensioning principles have been decided based on the listed assessments, the cost-effectiveness of different overvoltage protection schemes can be assessed. When the most cost-effective FSC overvoltage protection scheme has been specified, the TRV risk assessment and management method should be applied. In the Finnish series compensated network, gapless overvoltage protection was found cost-effective for most of the FSCs, and the extra circuit breaker TRV test requirements were specified in order to manage TRV risk in series compensated lines.

VI. References

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