Enhancement of the Reliability of Extra and Ultra High Voltage Transmission Systems

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Abstract-- **Single-pole auto-reclosing is an approved method to enhance the reliability in transmission systems. But with increasing system voltage, the maximum line length, for which a common single-pole auto-reclosing is successful, decreases. Therefore this paper will show how single-pole auto-reclosing can also be applied in extra and ultra high voltage transmission systems, by extending the system with high-speed grounding switches or with four-legged shunt reactor schemes. The operation mode of both will be illustrated.**

Index Terms -- **four-legged shunt reactor scheme, high-speed grounding switches, secondary arc current, single-pole auto-reclosing**

I. INTRODUCTION

A high rate of economic growth in the Asia Pacific leads to an increasing power demand. Hence new power generation plants have to be built to satisfy the expected consumption. As the economic growth shows an accelerated pace with several hundred of GW in the next years, only large power plants, like hydro power, nuclear or coal plants, can fulfill the requirements. These new generation centers cannot be constructed on arbitrary locations, because they are dependent on the energy deposits. The power has to be transmitted from the generation centers to the load centers over distances up to 1000 km or more.

In the same way as the generation capacity grows, the transmission capacity must increase. New transmission lines and corridors are installed at system voltages of 500 to 1200 kV AC and up to 800 kV DC. In this paper further considerations are only taken on the AC transmission systems. They consist of single- or double-circuit lines and show a radial or open ring structure.

Considering the high transmitted power and that the transmission system is not meshed, a high reliability of each transmission line is of major importance. Therefore any unnecessary tripping of the line should be avoided.

As in transmission systems the majority of faults are line-to-ground faults (more than 90%) [1], a common method to handle this kind of fault is a single-pole auto-reclosing (SPAR). When the fault is an arc fault, a successful SPAR is achieved, when the secondary arc current extinguishes during the dead time. Therefore the SPAR enhances the reliability of transmission systems by clearing line-to-ground faults and thereby keeping synchronism and maintaining more than the half of the nominal power flow during fault clearing.

II. ANALYZED TRANSMISSION SYSTEMS

Only extra and ultra high voltage transmission systems have the capacity which is required with the increasing power demand. The generation and the load center are connected by overhead (OH) lines which show a radial structure and consist of a single-circuit line or double-circuit line. This network configuration is mentioned as a bulk power transmission system [2] and a simplified illustration is given in Fig. 1.

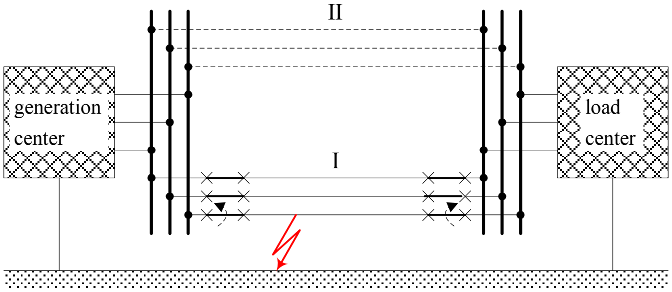

Fig. 1. Bulk power transmission system consisting of a single- (I) or double-circuit (I+II) line during SPAR

The reliability of the transmission system is of major importance for the bulk power system. Any unnecessary tripping of the OH lines must be avoided. But in case of a short-circuit, the line has to be tripped, to protect the system components from damages caused by the high currents. For OH lines the dielectric recovery of the insulation is self-restoring, after the interruption of the current and if the fault is not a permanent fault. Therefore the line can be switched on again and the power transmission is restored. This approach is called auto-reclosing.

It has to be distinguished between the three-pole auto-reclosing (TPAR) and the SPAR.

III. AUTO-RECLOSING SCHEMES

The advantage of the auto-reclosing in case of fault clearing, is to make use of the dielectric recovery of the insulation. Therefore the primary arc current, which is feeded by the fault current, extinguish by opening the circuit breakers of the faulted phase at both line ends. The ionized arc channel offers the secondary arc current the possibility to flow. This current is influenced or induced by capacitive or inductive coupling from the two energized (healthy) phases in case of

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SPAR or by the coupling to the parallel circuit in case of SPAR as well as TPAR. Only if the secondary arc current extinguish during the dead time a successful auto-reclosing is possible. Otherwise the line circuit breakers will switch on an arc path and therefore the fault current is flowing again. In Fig. 2 the operation mode of an successful auto-reclosing is given schematically.

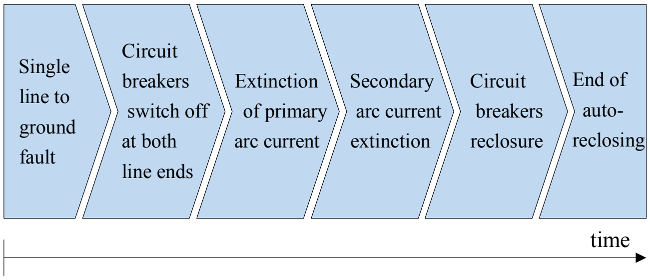

Fig. 2. Operation mode of auto-reclosing

A. Three-Pole Auto-Reclosing

In case of TPAR all phases of the faulted transmission line are tripped at both line ends, even if there is a single line to ground (SLG) fault.

Hence there is no inductive and capacitive coupling between the faulty and healthy phases for a single-circuit transmission system and therefore the dead time of the auto-reclosing has only to be as long as it takes to recover the insulation of the primary arc path. A disadvantage of the TPAR is that the energy transport is completely interrupted during the TPAR. Especially for long transmission systems with radial structure, this may lead to the loss of synchronism of the connected network, even if the dead time of TPAR is in the range of 0.3 to 0.5 s [3]. So for long extra and ultra high voltage transmission systems, the TPAR is not a proper medium to enhance the reliability of the transmission system, because of the probable loss of the system stability during the TPAR.

In case there is a double-circuit transmission system there is still power transmission over the parallel circuit possible and so the loss of synchronism during the TPAR is unlikely. Because of the parallel system there can be an inductive and capacitive coupling depending on how the two systems are transposed. In bulk power transmission systems transposition is a common practice because of the long line length. In Fig. 3 and Fig. 4 there are two different possibilities for transposition [4] shown.

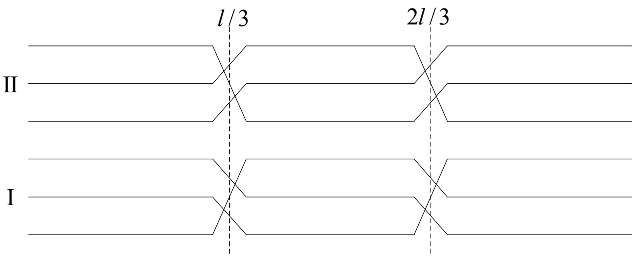

Fig. 3 γ-transposed double-circuit line

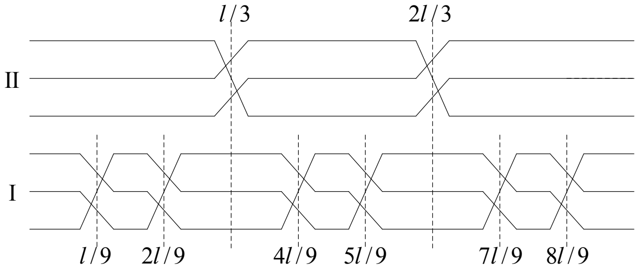

Fig. 4 β-transposed double-circuit line

For the double-circuit β-transposed line there is no coupling from the healthy system during the TPAR. Generally the transmission systems are not β-transposed, because of the extensive configuration. They are usually γ-transposed and therefore exists a coupling between the two systems when the TPAR takes place and the secondary arc current is feeded by the healthy system. In Fig. 5 the secondary arc current dependent on the line length is plotted for different voltage levels of the transmission system. The calculation for Fig. 5 and the following figures is done by a numerical calculation in symmetrical components described in [5] and based on the line data from [3] included in the appendix. The arc resistance is not considered which leads to a higher secondary arc current.

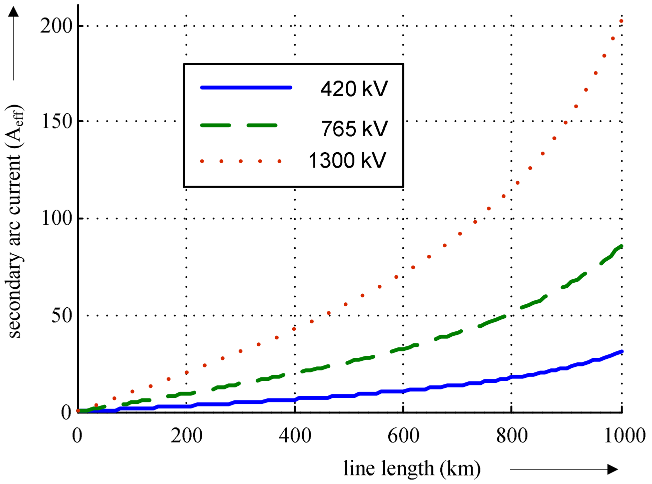

Fig. 5 Secondary arc current for γ-transposed double-circuit during TPAR for different voltage levels and line configurations

From Fig. 5 can be seen that for bulk power transmission systems with high voltage levels and long lines the secondary arc current increases and for this an extinction in usual dead times is not anymore possible. With a prolonged dead time of the TPAR the possibility of system instability comes, especially when the second system is switched off.

For this reason the application of TPAR in bulk power transmission system is not reasonable when the reliability of the system is considered.

The coherence between dead time and magnitude of the secondary arc current will be explained in the following chapter.

B. *Extinction of Secondary Arc Current for SPAR*

The extinction of the secondary arc current and its time duration depend on different parameters like:

- Magnitude of primary short circuit current and its clearing time
- Wind velocity
- Magnitude of secondary arc current
- Magnitude and transient response of the voltage at the fault location after extinction of the secondary arc

The burning time and the magnitude of the primary short circuit current affect essentially the burning time of the secondary arc current as well positive and negative. If there exist a highly ionized channel, because of the long duration and magnitude of the primary arc current, the secondary arc finds an advantageous condition. But on the other side there is a good chance of natural extinction because of the thermal boost and the enlargement of the primary arc path. In high voltage networks the primary arc current is expected to be 5 kA or higher and the clearing time is 50 to 80 ms. Hence the secondary arc extinguishes if its magnitude is under 10 to 20 A within the dielectric recovery time of the primary arc channel [3].

If the secondary arc current is larger the wind velocity, the magnitude of the secondary arc current, the dimension of the secondary arc channel and the magnitude and transient response of the voltage at the fault location after arc extinction determine the burning time. Reference [3] comes to the conclusion that wind velocity, which is a stochastic parameter, and the magnitude of the secondary arc current are the dominant parameters for the burning time. Laboratory and network tests proofed the interrelationship between the current magnitude and the burning time and are illustrated in Fig. 6.

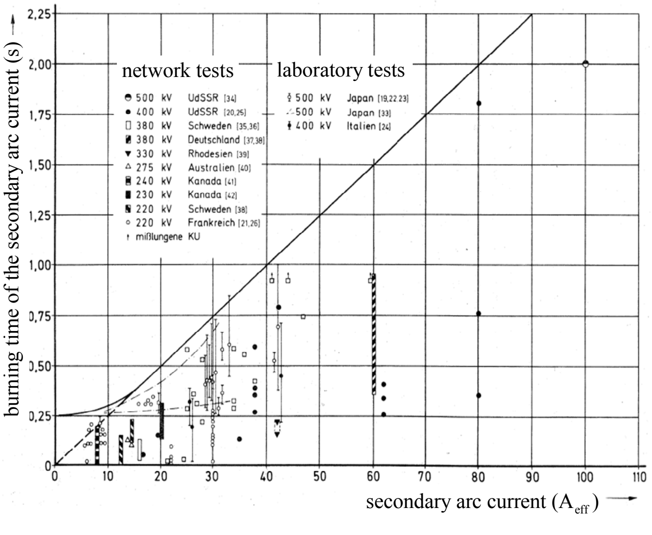

Fig. 6 Measured burning time of secondary arc current for SPAR in high voltage networks from 220 kV to 500 kV [3]

From Fig. 6 can be concluded that there is a linear relationship between the burning time of the secondary arc current and the current magnitude which can be computed according to [5]. Therefore the required dead time for the SPAR is obtained for OH lines of any length. The dead time is made up by the burning time of the secondary arc current and the de-ionizing time of the arc channel. The de-ionizing time is assumed to be in the range of the time for TPAR and therefore between 0.2 to 0.3 s. This estimate is on the sure side, because the secondary arc current is much lower than the primary short circuit current. The burning and de-ionizing time together designate the dead time of the SPAR and this time t_{dead} can be calculated for a given secondary arc current I_{sec} according to

$$t_{\mathrm{dead}} \geq 0.25\left(0.1 \cdot \frac{I_{\mathrm{sec}}}{\mathrm{A}} + 1\right)\mathrm{s} \qquad (1)$$

Otherwise from (1) the acceptable magnitude of the secondary arc current can be evaluated when the dead time is provided by network stability calculations. If for example the maximum dead time is 1.5 s to ensure stability, the maximum amplitude of the secondary arc current for a successful SPAR is 50 A.

Equation (1) is found empirical based on the network and laboratory tests according to Fig. 6. The results originate from tests with voltage levels up to 500 kV. But also in higher voltage levels (1) can be applied. Russian field tests in a 1200 kV line [6] show that with higher voltage level and therefore an increasing arc gap, the secondary arc current extinguish faster than predict by (1). The reason for this is the non-uniformity of the arc along its length and with it the internal exchange of energy between parts inside the arc column. But until now, the physical description of the arc in an analytical way is not possible and therefore network and laboratory tests are indispensable to forecast the necessary dead time for SPAR.

Hence the relationship between the dead time of the SPAR and the magnitude of the secondary arc current is assumed according to (1) for all voltage levels and line lengths.

IV. INTERRELATIONSHIP BETWEEN SUCCESSFUL SINGLE-POLE AUTO-RECLOSING, LINE LENGTH AND VOLTAGE LEVEL

The previous chapter shows the relation between the secondary arc current magnitude and the dead time of the SPAR. For a given dead time, an acceptable current magnitude is designated. The success of the SPAR is likely if the value of the secondary arc current calculated for a network is lower.

The current is induced by the healthy lines of the transmission system due to capacitive and inductive coupling. The numerical calculation is done with symmetrical components and based on the distributed parameter line model. In this calculation the capacitive and inductive coupling cannot be distinguished. Therefore in the following chapter a simplified calculation is introduced to help understanding.

A. *Simplified Calculation of Secondary Arc Current*

To get a better impression of the capacitive and inductive induced current during the SPAR, the current value is calculated with a simplified model of a single-circuit line according to Fig. 7. The capacitive coupling is given by the capacitance per unit line length $C_{\mathrm{c}}^{'} = \left(C_{1}^{'} - C_{0}^{'}\right)/3$ and the inductive coupling with the potential difference U'_{ind}.

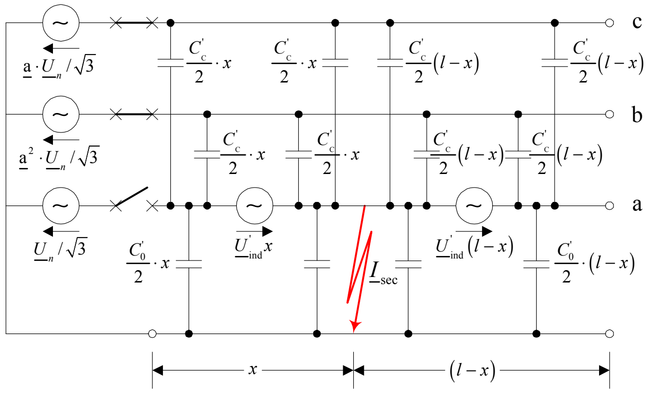

Fig. 7 Simplified equivalent circuit diagram of the transmission system for a single-circuit line during SPAR with variable fault location *x*

From Fig. 7 the influenced current $I_{\text{sec}}^{\text{inf}}$ is given as

$$I_{\text{sec}}^{\text{inf}} = \frac{U_{\text{n}}}{\sqrt{3}}\cdot\omega\cdot C'_{\text{c}}\cdot l \tag{2}$$

and the induced current $I_{\text{sec}}^{\text{ind}}$ as

$$I_{\text{sec}}^{\text{ind}} = U'_{\text{ind}}\left(\frac{l}{2}-x\right)\cdot\omega\cdot\left(C'_0+2C'_{\text{c}}\right)\cdot l \tag{3}$$

In (3) the induced voltage U'_{ind} depends on the total current of the two healthy lines and the inductive coupling between the lines and the overhead earth wire. Assuming that

- the line was naturally loaded before the fault (assumption for all further calculations in this paper)
- the voltage phasors of the positive-sequence system of the joined networks are constant in absolute value and phase during the disturbance
- the magnetic coupling between phase-to-phase and phase-to-earth does not differ too much

the induced voltage can be calculated as

$$U'_{\text{ind}} \simeq \frac{L'_0/L'_1-1}{2L'_0/L'_1+1}\cdot\omega\cdot\sqrt{L'_1C'_1}\cdot\frac{U_{\text{n}}}{\sqrt{3}} \tag{4}$$

with L'_1 and L'_0 positive- and zero-sequence inductance per unit length

From (2), (3) and (4) can be seen that both the influenced and the induced part of the secondary arc current increase proportional with the system voltage. But the influenced part is independent from the fault location *x* whereas the induced part decreases linear from the line ends to the middle of the line. Fig. 8 shows the results for the secondary arc current with an exact numerical calculation (1 solid line) and with simplified calculation (2 lines), according to equations (2) to (4). The considered line is a 765 kV single-circuit line α-transposed with a line length of 500 km. The α-transposition of the single-circuit line is carried out like the transposition of one system of the γ-transposition in Fig. 3. The fault location varies from the line beginning to the end. It can be seen that for the simplified calculation, the influenced current $I_{\text{sec}}^{\text{inf}}$ is constant all over the line and the induced current $I_{\text{sec}}^{\text{ind}}$ is at its maximum for a fault at the beginning or the end of the line. Using the exact numerical calculation it cannot be distinguished between capacitive and inductive coupled secondary arc current, but therefore the line resistance and reactance are considered and this leads to the highest secondary arc current for a fault location at the beginning of the line. Further on the fault location of the line-to-ground fault is assumed to be at the line beginning to get the worst case condition for SPAR.

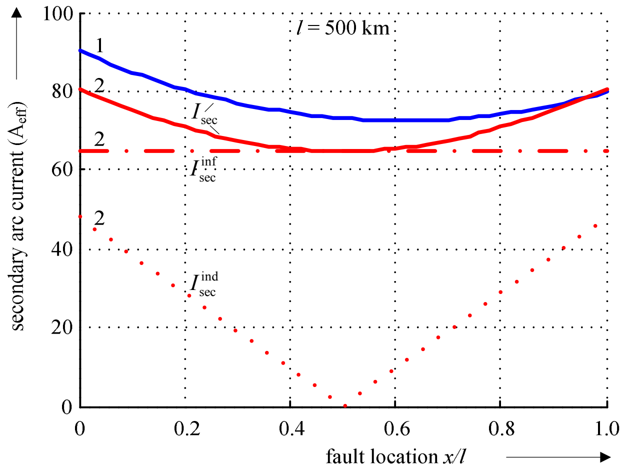

Fig. 8 Secondary arc current I_{sec} depending on the fault location on the 765 kV single-circuit line;
1: numerical calculation [5]; 2: simplified calculation

According to (1) and for an allowed dead time of the SPAR of 1.5 s the acceptable secondary arc current value for a successful extinction is 50 A. In the considered case of Fig. 8 the value of I_{sec} for worst case condition is about 90 A, therefore the probability of successful auto-reclosing is low. The reason for this is the voltage level and the line length.

The influenced part of the secondary arc current depends linear on the line length *l* according to (2) and the induced current increases by l^2 according to (3) and (4). In Fig. 9 calculation results for the secondary arc current for the same overhead line used in Fig. 8 are plotted, depending on the line length and a fault location at the line beginning.

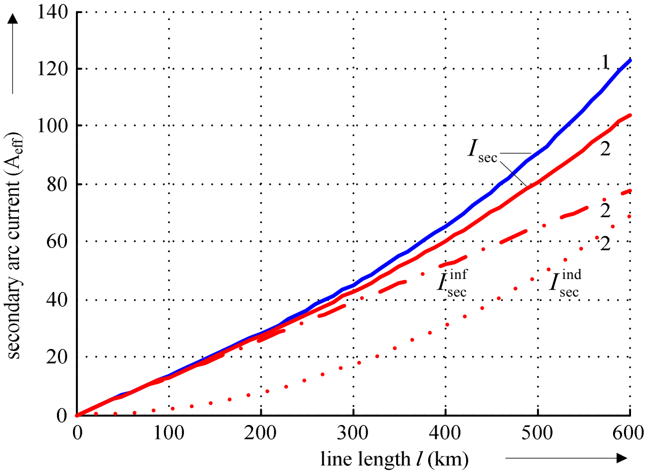

Fig. 9 Secondary arc current depending on the line length *l*

The calculation results show that for a line length of 320 km the SPAR is likely within a dead time of 1.5 s. It can also be seen from Fig. 9 that the difference between the exact numerical calculation and the simplified calculation increases strongly for a line length longer than 300 km. The reason therefore is the simplified line model in Fig. 7 used for the calculation. But with the simplified model calculation the influenced and induced parts of the current can be seen clearly and it is also obvious that for a line length shorter than 200 km the secondary arc current is mainly dominated by the influenced current part. For longer lines the induced current part increases faster and now it depends on the fault location how the current fractions refer to each other (see also Fig. 8). Until further notice the exact numerical calculation is used in this paper.

B. *Influence of Transposition and Conductor Configuration*

The previous chapter shows that the secondary arc current increases with line length and system voltage. But until now the influence of the conductor configuration and the transposition were not considered. Coupling capacitance C_C' is for a conductor configuration of triangular shape higher than for a horizontal configuration. That applies too for the inductive coupling between the conductors. In this paper all double-circuit line data, used for calculation, are based on triangular conductor configuration for each system but differ in the way of transposition. For a system voltage of 765 kV the influence of conductor configuration and transposition on the secondary arc current is shown in Fig. 10 depending on the line length. The double-circuit systems lead to a higher current value, because of the higher coupling capacitance C_C'. It is also remarkable that the completely symmetrical conductor configuration of the γ-transposed system causes a higher current value than the β-transposed system. The reason for it lies in the reduction of the influenced current by the coupling capacitance between the faulty phase and the healthy system. For a γ-transposed system this capacitance is zero and therefore no reduction is obtained [3].

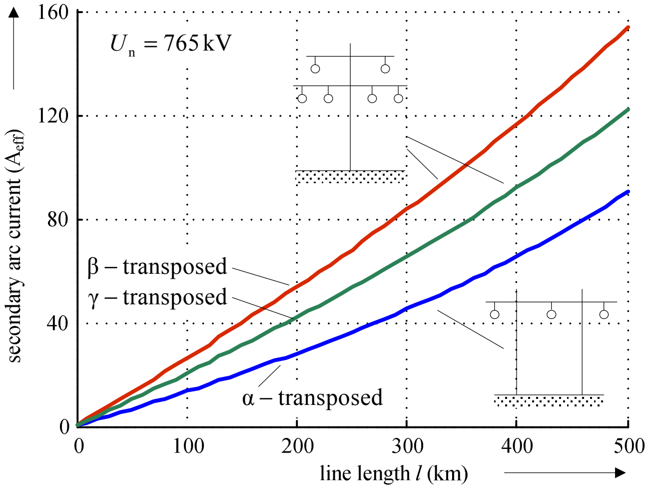

Fig. 10 Influence of conductor configuration and transposition on the secondary arc current for variable line length

C. *Maximum Line Length for OH Lines with SPAR*

As the secondary arc current increases strong with the system voltage level and the line length, the value of 50 A, which is claimed for successful SPAR within a dead time of 1.5 s, is exceeded for extra and ultra high voltage systems on comparatively short lines. In Fig. 11 calculation results for the maximum line length are plotted for different operational voltages and transpositions. A trend line is inserted by interpolation and it can clearly be seen that for bulk power transmission systems with operational voltages higher than 750 kV and line lengths of several hundreds of kilometers the SPAR cannot be used for enhancement of the reliability, because the secondary arc current will not extinguish within the dead time. In particular transmission systems with double-circuit lines have a reduced maximum line length of around 150 km compared with single-circuit lines. Only on rather short lines the SPAR will operate successful otherwise measures have to take into consideration to elongate the maximum line length.

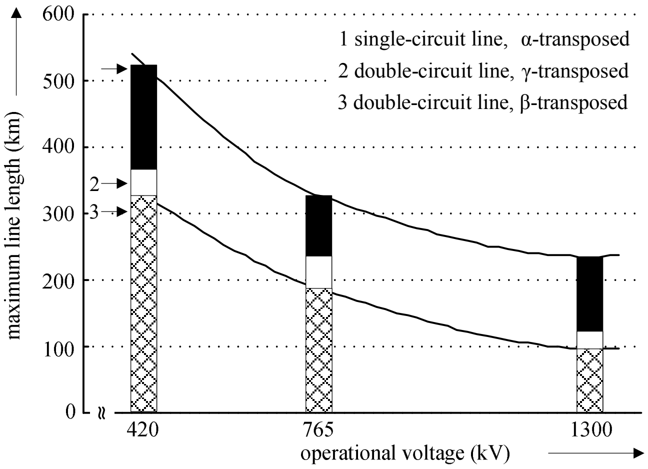

Fig. 11 Maximum line length for successful SPAR within a dead time of 1.5s

V. ELONGATION OF THE MAXIMUM LINE LENGTH FOR SUCCESSFUL SPAR

The previous chapter shows the limitation of the maximum line length for which the SPAR operates successful in extra and ultra high voltage networks. To make use of the benefits of the SPAR to increase the reliability of transmission systems even for longer line lengths, measures have to be taken to ensure successful extinction of the secondary arc current during the dead time of the auto-reclosing. These measures can be in the use of the four-legged shunt reactor scheme or the use of high-speed grounding switches (HSGS).

A. *Shunt Reactor Compensation*

Until now it was not considered that in bulk power transmission systems shunt reactors are used for compensation of the high reactive power demand and to avoid underexcitation of the generators. Especially after installation of the transmission system when the transmitted power is low or for ultra high voltage lines during the whole operation time, because they are normally operated with natural load or lower, the shunt reactors have the function to compensate the power demand of the positive-sequence capacitance C_1. The shunt reactors in extra and ultra high networks are realized as single phase units and normally located at the line beginning and end. They are connected directly to the line because beside the voltage reduction they restrict the overvoltages during load shedding and switching on no-load lines. A simplified network which illustrates the connection, is given in Fig. 12.

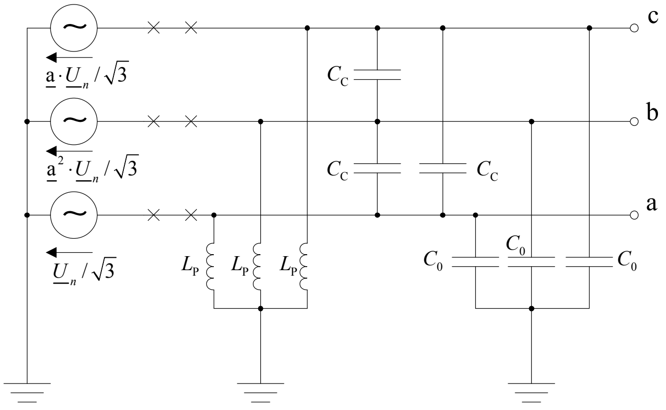

Fig. 12 Simplified network with shunt reactors connected directly to the transmission line at the beginning

The value of the reactor L_P depends on the compensation degree k which is normally chosen between 60% and 80% [2]. The following equation explicates the relation between shunt reactor value, compensation degree and positive-sequence of the line capacitance C_1 and coupling capacitance K_1.

$$L_P = \frac{2}{k\cdot\omega^2\cdot\left(C_1'-K_1'\right)\cdot l} \tag{5}$$

The shunt reactors reduce the inductive part of the secondary arc current during the SPAR compared with the SPAR without shunt reactors in IV. They have no affect on the influenced current part [3]. In Fig. 13 the maximum line length is plotted for the same network configuration as in Fig. 11 but with a shunt reactor compensation degree of 60%.

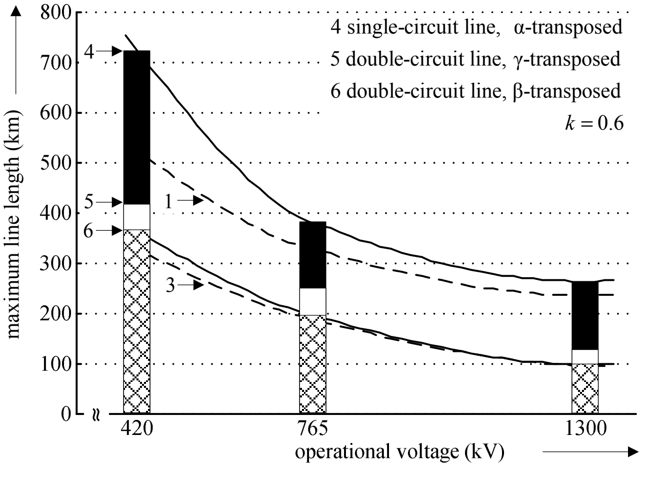

Fig. 13 Maximum line length for successful SPAR within a dead time of 1.5 s with shunt reactor compensated line, line 1 and 3 correspond to Fig. 11

It appears that through the shunt reactor compensation the acceptable line length for successful SPAR within a dead time of 1.5 s increases. A comparison of the single-circuit line (curve 1 without and curve 4 with shunt reactor compensation) shows that in particular for operational voltages of 420 kV the maximum line length increases intensely. The cause therefore is that for this transmission system the permissible line length without compensation was already in the range of 500 km and from this line length upwards the inductive part of the secondary arc current dominates more and more the value of I_{sec} relative to the influenced part (see also Fig. 9). In higher voltage levels or for double-circuit lines where the acceptable line length lies in the range of 300 km without compensation, the influence of shunt reactor compensation to extend the acceptable line length is rather low, because for these line lengths the influenced part of the secondary arc current dominates. This part is not reduced by the installation of the shunt reactors.

B. *Four-Legged Shunt Reactor Scheme*

By the installation of an additional reactor in the star point of the line compensating reactors it is possible to reduce the influenced part of the secondary arc current which is caused by the capacitive coupling between the conductors. Fig. 14 shows the operation method.

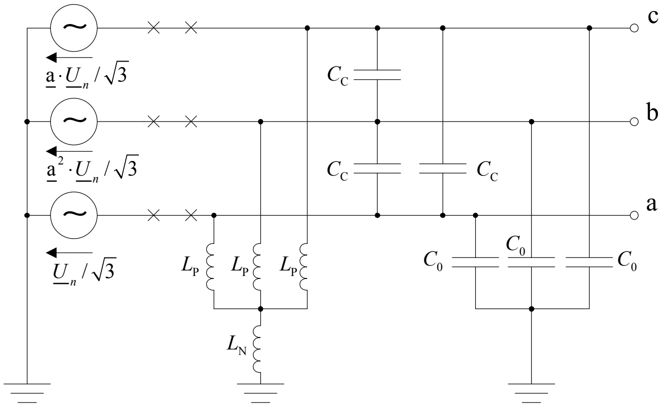

Fig. 14 Simplified network with shunt reactors connected directly to the beginning of the transmission line with additional reactor in the star point

The value of the additional reactor in the star point L_N depends on the compensation degree k, the positive- and zero-sequence value of the line capacitances and for a double-circuit line on the value of the positive-sequence coupling capacitance K_1. The dimensioning is done by the following equation:

$$L_N = \frac{1}{3}\cdot\frac{L_P\cdot m_0}{k-m_0} \quad \text{with } m_0 = \frac{C_1'-C_0'-3\cdot K_1'}{C_1'-K_1'} \tag{6}$$

For single-circuit lines and β-transposed double-circuit lines the value of K_1' is zero. Typical values of m_0 for the lines used in this paper are:

- 0.18 – 0.22 for single-circuit lines α-transposed
- 0.44 for double-circuit lines γ-transposed
- 0.35 – 0.39 for double-circuit lines β-transposed

For common compensation degrees of 60% to 80% and m_0 between 0.2 and 0.44 the following Table I gives the values of L_N related to L_P.

TABLE I
MATRIX FOR THE VALUE L_N REFERENCED TO L_P AND DEPENDING ON m_0 AND k

L_N/L_P	$m_0 = 0,2$	$m_0 = 0,35$	$m_0 = 0,44$
$k = 0,6$	0,167	0,467	0,917
$k = 0,8$	0,111	0,259	0,407

In Fig. 15 the maximum line length is plotted for the same network configuration as in Fig. 11 and Fig. 13 but with a shunt reactor compensation degree of 60% and an additional reactor in the star point dimensioned according to (6).

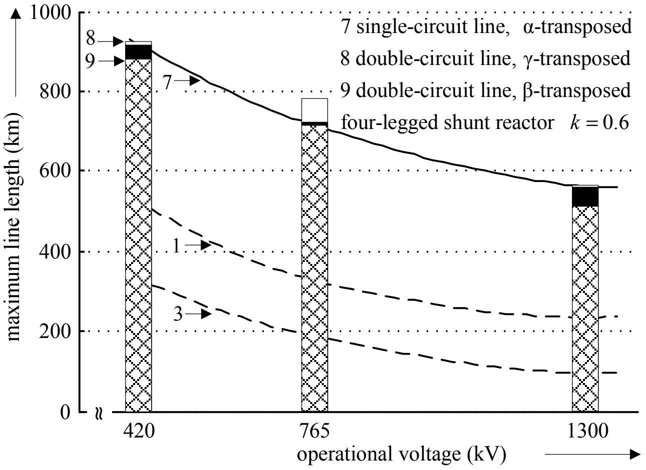

Fig. 15 Maximum line length for successful SPAR within a dead time of 1.5 s with shunt reactor compensated line and additional neutral reactor in the star point, line 1 and 3 correspond to Fig. 11

From Fig. 15 can be concluded that the installation of the four-legged shunt reactor scheme contributes extensive in the elongation of the acceptable maximum line length to ensure successful SPAR. The comparison between curve 1 (not compensated network) and curve 7 (four-legged shunt reactor scheme), both for a single-circuit transmission system, shows the positive effect. The maximum permitted line length is nearly doubled. For double-circuit lines the elongation is still higher. It lies in the range of factor 3. The maximum line length is around 500 km for the β-transposed double-circuit line. For the other line configurations it is even longer.

So even for ultra high voltage transmission systems the SPAR is possible if the distance between switching stations does not exceed 500 km. Therefore the SPAR leads to an enhancement of the reliability of extra and ultra high voltage transmission system.

C. High-Speed Grounding Switches

If the length of the transmission system is longer than the permissible length for which SPAR with four-legged shunt reactor scheme is successful or if the transmission system consist of short lines and therefore no shunt reactor compensation is planned, HSGS is a proper method to extinguish the secondary arc current during the dead time of auto-reclosing. The operating sequence of HSGS is shown in Fig. 16 and is composed as follows:

(a) Primary arc is generated at the fault location when a fault occurs
(b) Secondary arc current caused by healthy phases and fault current is interrupted by circuit breakers
(c) HSGS are closed, then secondary arc is extinguished
(d) HSGS are opened
(e) Circuit breakers are closed after recovering of the insulation strength at the fault location

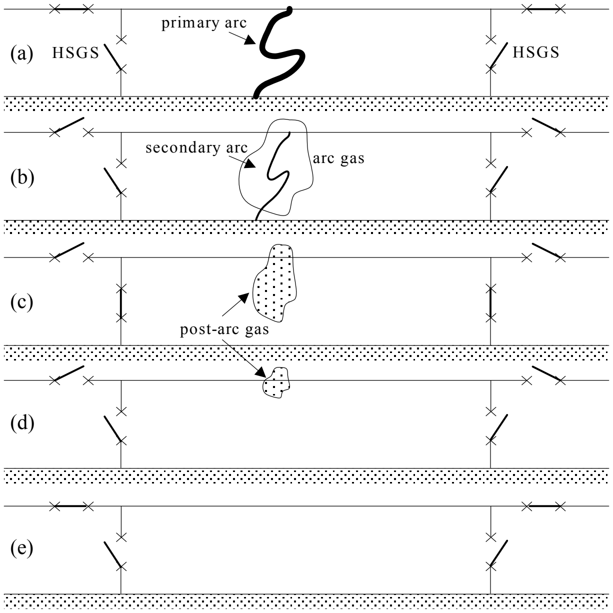

Fig. 16 Operating sequence of HSGS, illustrated for one faulty conductor

The extinction of the secondary arc when HSGS is applied is based on two effects. When the fault location is near the HSGS (line end or beginning) the arc path is short-circuited by the HSGS, so the voltage over the arc is very low and a stable electric arc is not possible. If the fault location is more in the middle of the line, two closed loops are formed with the HSGS and the arc path. The two instantaneous currents of the loops are opposed to each other in the fault path and thereby decrease the secondary arc current. This and the fact of the grounded phase at line beginning and end decreases the induced voltage, allows extinction of the secondary arc. Fig. 17 shows this demonstratively.

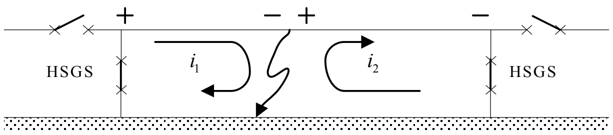

Fig. 17 Faulty phase during SPAR with HSGS and existing secondary arc current

Beside the four-legged shunt reactor scheme HSGS is a proper method to extinguish the secondary arc during the dead time of the SPAR.

VI. CONCLUSION

SPAR is an approved method to enhance the reliability of transmission systems. It makes use of the self-restoring ability of the insulation of OH lines after the fault is cleared. Therefore not only the primary fault current has to extinguish during the dead time of the auto-reclosing but also the secondary arc current. This current is feeded by the inductive and capacitive coupling from the healthy phases to the faulty phase. The extinction of the secondary arc depends on different parameters and a major parameter is the magnitude of the secondary arc current. The influence of the system configuration (single- or double-circuit line, transposition, line length, voltage level) on the magnitude shows this paper.

For bulk power transmission systems the maximum line length for which the secondary arc current extinguish within the dead time is in the range of 100 to 300 km when no compensation scheme or HSGS is applied. Through the HSGS or four-legged shunt reactor scheme the maximum line length can be elongated up to 500 km or more.

With these methods the benefits of SPAR on the enhancement of the reliability can also be used in extra and ultra high voltage transmission systems

VII. APPENDIX

TABLE II
LINE DATA USED IN THIS PAPER

operational voltage (kV)	420	765	1300
single-circuit line α-transposed			
L_1' (mH/km)	0,97	0,89	0,85
L_0' (mH/km)	2,16	1,96	1,89
C_1' (nF/km)	11,8	12,7	13,1
C_0' (nF/km)	9,2	9,9	10,7
R_1' (mΩ/km)	23,4	10,9	5,5
R_0' (mΩ/km)	70	61	58
double-circuit line γ-transposed			
L_1' (mH/km)	0,98	0,96	0,81
L_0' (mH/km)	2,84	2,61	2,44
C_1' (nF/km)	12,3	12,6	14,9
C_0' (nF/km)	6,9	7	8,3
R_1' (mΩ/km)	35	11	5,5
R_0' (mΩ/km)	124	95	94
M_1' (mH/km)	0,019	0,026	0,028
M_0' (mH/km)	(1,35-j0,28)	(1,3-j0,28)	(1,2-j0,28)
K_1' (nF/km)	0,24	0,42	0,53
K_0' (nF/km)	1,26	1,73	1,82
double-circuit line β-transposed same values as for γ-transposed, but M_1' and K_1' are zero			

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Mathias Ramold was born in Ansbach, Germany, on March 29, 1978. He received his Dipl.-Ing. degree in Electrical Engineering from the University of Erlangen in 2004. At present he is a scientific assistant at the Institute of Electrical Power Systems at the University of Erlangen-Nürnberg. His primary field of interest is the influence of dynamics on the design of protection systems and on the protection coordination. He is member of VDE and its associated section ETG.

Johann Jäger received the Dipl.-Ing. and Dr.-Ing. degrees in 1990 and 1996 in Electrical Engineering from the University of Erlangen respectively. From 1996 he was with the Power System Planning department at SIEMENS in Erlangen, Germany. He was working on different fields of FACTS devices, network planning, and protections in worldwide projects. Since 2004 he is in charge of a full professorship for Power Systems at the University of Erlangen. He is member of VDE/ETG, IEEE and CIGRE as well as convenor or member of several national and international working groups and task forces.