Simulation of load displacement in parallel lines using series connected tapped reactor

T. Wenzel   T. Leibfried

Institute of Electric Energy Systems and High-Voltage Technology
University of Karlsruhe
Karlsruhe, Germany
wenzel@ieh.uni-karlsruhe.de

Abstract - Different parallel transmission lines can be utilized when there is a power flow from a surplus generation area to a load centre in a meshed power grid. The current distribution in these lines depends on the inverse value of the line impedances. The current path with the lowest impedance will reach its maximum transmission capacity considerably earlier than the other parallel paths. It thus determines the maximum transmittable power, although the other parallel paths are not loaded to full capacity. There are different possibilities to influence the current distribution, for example using a phase shifting transformer (PST) or reducing the impedances of the partially loaded lines with series capacitors. Another possibility is a tapped reactor series connected to the overloaded line. The different taps are switched with circuit breakers. The current will be displaced into the other paths by increasing the reactors impedance. This paper presents a simulation model of power transmission with three parallel transmission lines, using PSCAD Software. A tapped reactor is inserted into the line with the least impedance. The simulation is carried out with different steady state load flows, and the respective effect on current distribution caused by varied reactor impedance is investigated. Furthermore, the stress on the components, for example the reactor and the circuit breakers, while changing the reactors impedance, is analyzed.

Keywords- **Simulation, Load Displacement, Series tapped reactor, Parallel transmission lines, PSCAD**

I. INTRODUCTION

One possibility of equal load distribution in parallel lines is to extend a shorter one electrically. This means, an additional reactor has to be inserted into it. Current will then transfer into lines with smaller impedances. Parallel lines connecting two network stations A and B typically have the same length and parameters. One can imagine a network configuration, where three lines are connecting two stations. While one of them connects A and B directly, the other lines are connected via other stations. This would mean that the indirectly connected lines are longer, depending on spatial arrangement. The described configuration which is explained in the following section is used in this paper. The implementation of the electrical network together with the tapped reactor in PSCAD is presented afterwards. Finally, the simulation results are discussed and the stress on the involved elements is presented.

II. CONFIGURATION OF ELECTRIC NETWORK

The investigated electric network is a simple two node system with system frequency of 60Hz. One node is a feeding point with a fixed voltage of $U_1 = 400$kV and zero phase shift, the second one is connected to a load with constant active and reactive power. Transformers are not incorporated in this investigation because only the high voltage grid is of interest. The transmission lines are represented as Pi-Sections with following parameter:

TABLE I
LINE PARAMETER

Quantity	Value	Unit
R'	0.0259	Ω/km
X'	0.366	Ω/km
C'	13.44	nF/km

These values are typical for high voltage four-wire transmission lines with a voltage level of 400kV. In order to determine the influence of different parameters on load distribution, the number of parallel lines, line length, and power factor of load were modified. The following approach was used in all cases:

A. Transmissions system length

All parallel transmission lines (2 or 3) connecting both nodes were set to the same length, which was modified from 30km up to 100km. The load was simulated with constant power factor and the apparent power was dimensioned so that all parallel lines were operating at full capacity. The maximum apparent power of a line was set to 1400MVA which is lower than in [1]. In a next step, length of only one line was changed while the load remained constant. Fig. 1 shows the loading of the shorter line. Different lengths of the whole transmission system where simulated. The number of parallel lines was set to three and the power factor of load was 0.95 inductive. As expected, the influence of variation of the length of one line is greater, if the whole transmission system is shorter. Finally, the length of the transmission system was set to 80km. This length is not too long, so it can be simulated as a Pi-Section with lumped elements.
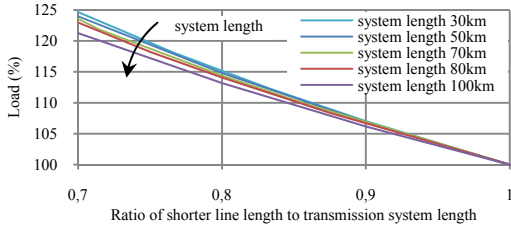
Figure 1. Capacity utilization of shorter line (different system lengths)

B. Load angle

Fig. 2 presents the influence of power factor on loading of the shorter line. Three parallel lines were assumed in this case. It can be seen, that it does not have a big impact on loading of the shorter line. To achieve low transmission losses and stable energy transmission, a power factor of 0.95 or higher has to be maintained.
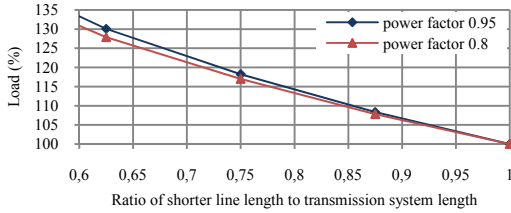

Figure 2. capacity utilization of shorter line (different power factor)

C. Number of parallel lines

A huge influence on load distribution by changing the length of one line is the number of parallel lines. Like before, the same approach was used with the same power factor of load, but this time the number of parallel lines was set to two and to three. The difference can be seen in Fig. 3. Finally, three parallel lines are assumed, as the impact is considerably greater.
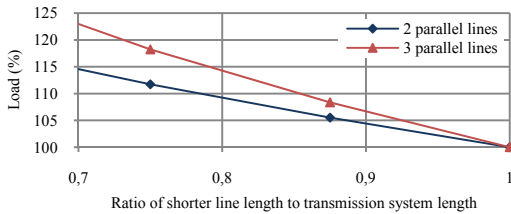

Figure 3. capacity utilization of shorter line (different number of lines)

D. Tapped reactor

One line is set to a length of 65km, so it is 18.75% shorter than the other two. The length difference of 15km is reasonably realistic and sufficiently high to overload shorter line by 13%. In order to compensate this length difference, the additional inductance requires approximately 23% of the total line inductance. A calculation with a load flow program resulted in a value of $L = 15$mH for the reactor. As the transmission lines are not always working at full capacity and in order to stepwise adjust the impedance, the tapped reactor is split into three reactor steps with $L_{step} = 5$mH respectively. All three reactor steps have taps, which can be short-circuited by switches. If one reactor step is bypassed,

line current will flow through the used switching element. Current is about $I_{400kV} = 2021$A with the above mentioned maximum apparent power of one line. The voltage across a reactor step is $V_{step} = X_{step} \cdot I_{400kV} = 3.8$kV. The reactive power of total reactor is $Q_{reactor} = 3 \cdot X_{reactor} \cdot I_{400kV}^2 = 69.3$Mvar. The transmission capacity of the investigated electric network can be increased about 11% if the reactor is inserted completely. The total transmittable apparent power is then $S_2 = 3747$MVA compared to $S_2 = 3377$MVA without reactor. In both cases it was assured that no line was overloaded.

E. Vacuum circuit breaker

A vacuum circuit breaker (VCB) is used as switching element in this investigation because of its ability to switch very often. Available breakers can handle currents up to 2.5kA and voltages up to 36kV. Considering the number of load replacements and the voltage and current requirements, this type of breaker seems to be adequate.

III. SIMULATION WITH PSCAD

The simulation tool used is PSCAD, which is a graphical interface to the EMTDC software.

A. Step Size

PSCAD works with a constant step size while running a simulation. This makes it difficult to investigate the long-term behavior and transient effects in one simulation. Hence different step sizes were used. A maximum step size of 20µs is necessary in order to incorporate the characteristics of the VCB model. The accordingly chosen step-size is mentioned in every section.

B. Simulation model of network configuration

Fig. 4 shows the simulation model created for this investi-gation. On the left side is the feeding point. It is modeled as an ideal voltage source. On the right side is the load which is represented by a fixed load element. Resistance and reactance of this element are calculated and changed depending on the voltage across them. Both nodes are connected by three parallel lines, whereby the shorter line is the middle one. All lines are modeled as Pi-Sections and the values of lumped elements are given in Table 2.

TABLE II
LUMPED ELEMENTS OF THE PARALLEL LINES

Line	Length in km	R in Ohm	L in mH	C in µF
L1, L3	80	2.07	77.67	1.08
L2	65	1.68	63.10	0.87

The tapped reactor with three reactor steps is serially connected to line 2. Therefore an element separates the three phases and joins them again around the reactor. Every reactor step is modeled as an inductance with $L_{step} = 5$mH and a resistance of $R_{step} = 10$mΩ. The VCB model is represented by a box labeled with "VS" and variable resistance at each step.
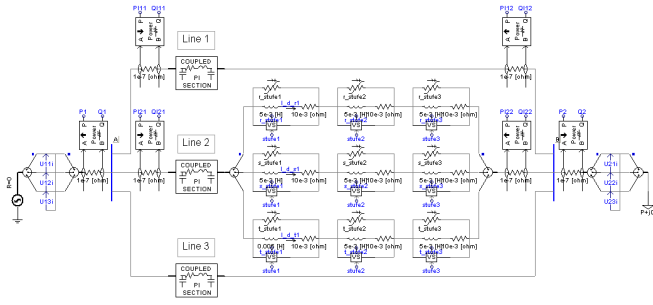
Figure 4. Simulation model of three parallel lines

Furthermore, active and reactive power is measured in the feeding node, in the load, in line 1 and in line 2. The power meters need a resistance to measure power which was set to a very small value of $0.1\mu\Omega$.

C. Configuration of VCB

The VCB model used in this investigation is from [2] where it was used to simulate a vacuum switch. However it can be used for modeling a VCB with new parameters.

TABLE III
PARAMETERS OF VCB

Parameter	Value	
maximum voltage	70	kV
Resistance (open)	80e-6	Ω
Resistance (closed)	1000e6	Ω
slope of dielectric strength	20	kV/µs
slope of dielectric recovery	7	kV/ms

The maximum voltage of the considered VCB is taken from data sheet [3]. The arc voltage is set to zero. It is only required if energy conversion in the tube has to be considered. A simulation with very high resolution has to be therefore performed. The chopping current isn't calculated by the formula given in [2], but set to a constant value of 5A. The Simulation results are then comparable and it represents the worst case scenario, as typical values of VCBs lie in the range of $2A - 3A$ [4]. The value of dielectric recovery slope is estimated.

IV. SIMULATION RESULTS

Fig. 5 shows the loading of the considered line and the effect of switching all reactor steps into it. It is no longer overloaded if all reactor steps are added. The simulation step size was set to $20\mu s$. The lower curve shows the moment of switching off all three VCBs in order to completely insert the reactor. The middle curve shows the loading of line 1 and line 3.
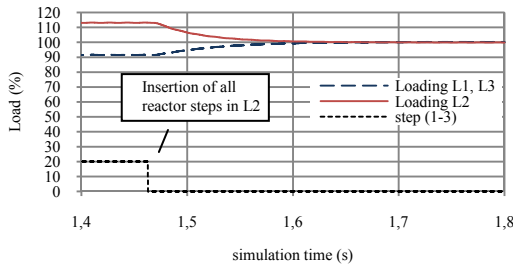

Figure 5. Inserting reactor in shorter line

It should be mentioned, that the process of load replacement takes place much faster than it seems in Fig. 5 due to the power meters which are working with a smoothing time constant of 50ms in order to smooth the measured powers sufficiently.

A detailed switching process of one reactor step into the line is shown in Fig. 6. The VCB across this step has to therefore be opened. In the upper graph, the voltages across VCB and the dielectric recovery of the gap can be seen. The lower graphs show the currents of VCB and of reactor step. As current through VCB falls below the value of chopping current, it is interrupted immediately and a transient recovery voltage (TRV) occurs. Its peak value and frequency of oscillation are dependent on the connected circuit. The TRV in phase r exceeds the dielectric strength of gap at $t = 1.452s$. This is the reason for the peak on the left side in the upper graph. After restriking, current will go on flowing until next zero crossing. As dielectric recovery increases rapidly with increasing contact distance, this effect doesn't occur again.

Fig. 7 shows the TRV of phase s in detail. The dashed line indicates the voltage in the same phase some periods later. The slope is $S = 0.114\,kV/\mu s$ which is below the typical dielectric strength slope of VCB (Table 3). The TRV peak value is $V_{peak} = 10.67kV$ which is 1.8 times larger than the peak value of the voltage across this reactor step. It is within the range of VCB parameter. The step size was in this case set to $4\mu s$. Actually, the oscillation isn't damped that strongly. This is a result of fixed load element, which calculates value of resistance and inductance dependent on voltage.
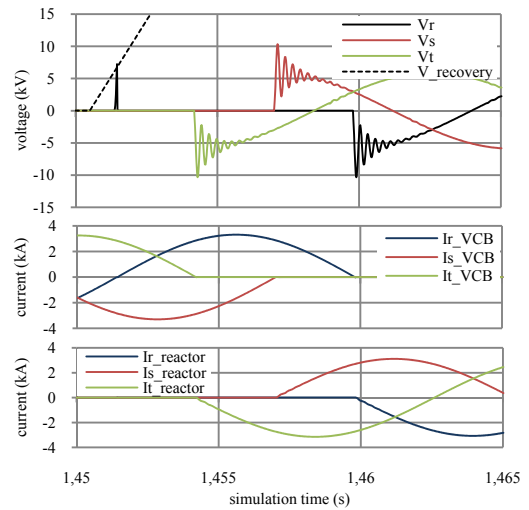

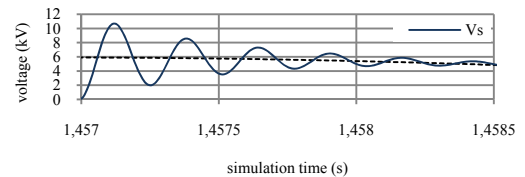Figure 6. VCB voltage and current while switching off

Figure 7. TRV in phase s

A simulation with constant resistance and inductance whose values were set to the same values as calculated by fixed load element at the moment of reactor insertion resulted in a weakly damped oscillation. The peak value however remained the same. In reality resistance of load and reactor are damping this oscillation.

A. Delayed switching of further VCBs

If another VCB is switched immediately after the first one, the voltage across it will superimpose on the voltage across the first one. But this effect depends on delay time. For no delay time, the voltages across the VCB don't have influence on each other. When delay time is at least so high that the second VCB can't successfully interrupt current, the resulting voltage peak will overlay to the TRV of the first VCB. This leads to much higher TRV peak values. The upper curve of Fig. 8 shows this effect in second phase of the first VCB. Two further VCBs were switched at the same time shortly after the first one in this case. In the lower graph, voltage across second VCB can be seen, which is similar to voltage across third VCB. The resulting TRV peak value across first VCB is 25.5kV. If only one VCB is switched additionally, peak value is 17.3kV. Peak value of unaffected TRV is 10.7kV. A step size of 4µs was used and delay time for switching further VCBs was set to 2.7ms. If they are switched after first VCB interrupted all currents successfully, the overlaid TRV on voltage across first one has a peak value, which is less than TRV peak in the beginning. This effect looks similar to the oscillation in Vt_step1 of upper graph at time 1.454s.

B. Short-circuit reactor step

A high stress on VCB appears when it short-circuits the reactor step. Dielectric strength decreases with decreasing contact distance. At the moment of ignition-through, voltage across VCB is forced to nearly zero and the reactor current starts to decay with a time constant of $\tau = L_{step}/R_{step} = 0.5s$. This decaying circulating current superimposes on current through VCB, thus causing a current with double amplitude in the worst case scenario. Fig. 9 shows currents of reactor step and of respective VCB. Further investigations are necessary to clarify the possibility of VCB to handle this stress. The resistance of reactor step (10mΩ) has a very small value. Higher values would reduce time constant and therefore reduce time of stress with higher current amplitudes.

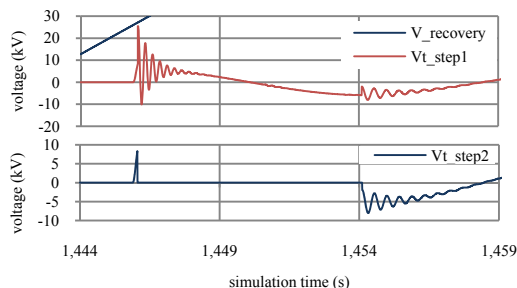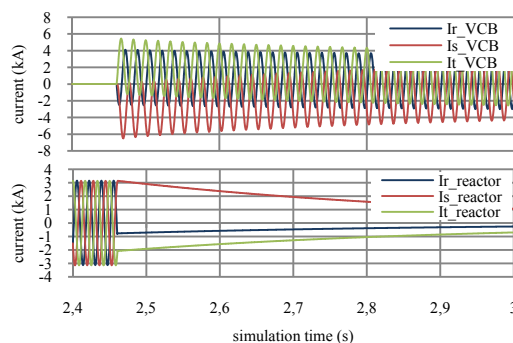Figure 9. VCB and reactor step current while switching on

C. Short-circuit on load side

It should be pointed out, that in case of short-circuit on the load side, the accurate operation of VCB is in certain circumstances not guaranteed. Line current in this case will reach comparatively high values. If there is a controller, which responds very fast and is going to increase inductance of reactor, VCB isn't able to interrupt this high current, because TRV peak would always exceed maximum dielectric strength. This leads to high thermal impact and finally to destruction of VCB.

V. CONCLUSIONS

Principally, a tapped reactor can force equal load distribution in parallel lines by extending a shorter one electrically. But the VCB which short-circuits the respective step has to handle multiple stresses. This is on the one hand a TRV with higher amplitude, namely when VCB is switched off in order to insert the inductance, and on the other hand very high currents in case of short-circuiting the reactor step. The TRV voltage peak should not overstress VCB if the inductance of one reactor step is well dimensioned. Several contributing parameters should be taken into account such as number of steps of tapped reactor, maximum line current and line parameter. The stress with high currents shortly after short-circuiting a step is more critical. With a higher reactor resistance, time constant of decaying current would be smaller, so that stress with high current amplitudes would be in a range, which VCBs are able to handle. Further investigations are necessary and will be accomplished.

REFERENCES

[1] D. Oeding, B. R. Oswald, "Elektrische Kraftwerke und Netze", 6th ed., Springer-Verlag, Berlin Heidelberg, New York, 2004
[2] T. Wenzel, T. Leibfried, D. Retzmann, "Dynamical simulation of a Vacuum Switch with PSCAD", 16th Power Systems Computation Conference, July 2008, Glasgow, Scotland
[3] Siemens, "Vakuum-Leistungsschalter 3AH2/3AH4", Katalog HG 11.04, 2007
[4] Siemens, "Vakuum-Schalttechnik fuer die Mittelspannung", Katalog HG 11.01, 2007
[5] H. J. Lippmann, "Schalten im Vakuum – Physik und Technik der Vakuumschalter", Berlin, Offenbach, VDE-Verlag GmbH, 2003
[6] "EMTDC - The Electromagnetics Transients & Controls Simulation Engine", User's Guide, Manitoba HVDC Research Centre Inc., 2005
[7] "PSCAD - Electromagnetic Transients", User's Guide, Manitoba HVDC Research Centre Inc., 2005

Figure 8. Delayed switching of further VCBs