POSSIBLE APPLICATIONS OF A TAPPED REACTOR SERIES CONNECTED TO A TRANSMISSION LINE IN THE HIGH VOLTAGE GRID

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Abstract: This paper points out possible applications of a tapped reactor, which is series connected to a HV transmission line. The different taps of the reactor can be short-circuited by switching elements in order to achieve a stepwise adjustable impedance. Vacuum Circuit Breakers (VCBs) are used in this case as switching elements as they can be switched more often without maintenance compared to other circuit breakers. The switching frequency is rather strongly limited by the mechanical properties of the VCBs. Hence, the application range seems to be limited to slower processes for example the load displacement in a meshed grid. In order to extend the application range to faster events, this paper describes an approach where more VCBs are switched in parallel to each other. Hence a higher periodically switching ability could be achieved. A possible application therefore is the damping of power oscillations, which can occur due to disturbances in electrical power systems. The electrical stress on the VCBs and the tapped reactor is investigated in this study for every regarded case. The simulation is carried out with PSCAD.

1. INTRODUCTION

The idea is to create a cost-effective device which is mechanically switched and to investigate its possibilities in an electric energy system. Due to the slow switching operation sequence of VCBs, the applications seem to be limited to slow processes like the load displacement in parallel transmission lines. This paper presents a way to deal with the above mentioned disadvantage by switching more circuit breakers parallel to each other in order to extend the application range. The basic principles of power oscillations and how to damp them with a series reactor are figured out in the following section. Afterwards the electrical circuit used for simulation is presented. Finally the electrical stress on the tapped reactor and the VCBs is assessed for power oscillation damping and load displacement and the next steps are discussed.

2. POWER OSCILLATION DAMIPING WITH A SERIES REACTOR

2.1. Power oscillations

Power oscillations occur due to disturbances in electrical networks. While there is an unbalance between the mechanical power of a synchronous machine and the electrical power which it transmits into a grid, the rotor of the generator speeds up or slows down. Because of the high moment of inertia, this process can take up to some ms without loss of synchronism. The load angle oscillates around the stationary value and a power oscillation appears. The following equation shows the relationship between the active power and the load angle.

$$P = \frac{V_S \cdot V_r}{X} \cdot \sin\delta \qquad (1)$$

Where: V_S, V_r voltages at receiving and sending end
X respective line impedance
δ phase difference between V_S and V_r

Generally the power oscillation is damped by the damper windings of the synchronous generator and by power system stabilizers but in some cases, the damping is insufficient. Additional damping is then necessary in order to return into a stable operation point. Figure 1 shows the transmittable power before, while and after a short-circuit in a transmission system over the load angle.

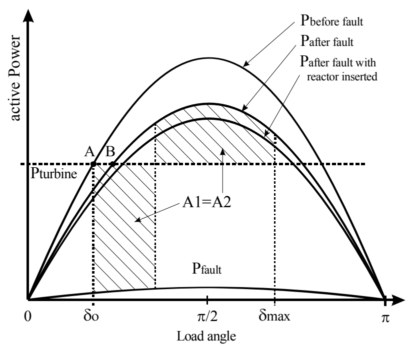


Figure 1: Transmittable power over load angle.

The intercept point A at δ_0 marks the steady state operation point before the short-circuit. While the short-circuit occurs the demand of electrical power is lower than the turbine power so the rotor accelerates. The change of kinetic energy complies to area A1 [2]. After eliminating the short-circuit the demand of electrical power is higher than the turbine power because of larger load angle. The rotor decelerates. The maximum load angle is reached when the released kinetic energy is equal to the absorbed energy. The power curve after the fault has smaller amplitude than the curve before the fault because of a line outage in the regarded case. The higher the decelerating area A2, the lower the maximum load angle will be. But at the point with maximum load angle, the rotor continues decelerating because the electrical power demand is still higher than the turbine power. This process goes on into the other direction and the load angle oscillates around the new stationary point B until the oscillation has decayed.

2.2. **Tapped reactor**

If a reactor or a step of a tapped reactor is inserted into the line, the power curve has a lower maximum, so the rotor will not go on decelerating that much as without reactor. But that requires an insertion of the reactor in moment of maximum load angle δ_{max}. It must not be inserted earlier because otherwise it would reduce the decelerating area A2 and a higher load angle would result, which could lead to instability. At the power minimum, the reactor has to be removed again in order to damp the oscillation sufficiently. This process can be repeated, until the remaining oscillation is small enough. It can be seen from Figure 1 that it is not possible to stabilize an unstable system with a reactor because it can only decrease the decelerating area.

The maximum power oscillation frequency is assumed to be $f = 1\text{Hz}$ in this investigation. Only one step of the tapped reactor is used and the inductance is set to different values which are mentioned in the respective sections. The quality factor is set to 190. The reactor has to be inserted and removed every 0.5s hence it can be short-circuited by VCBs.

2.3. **Vacuum Circuit Breakers**

Available VCBs can handle currents up to 2.5kA and voltages up to 36kV. Considering the number of switching operations and the voltage and current requirements, this type of breaker seems to be adequate. The tube needs maintenance after 30.000 switching operations, the mechanical part after 10.000 switching operations [1]. The typical rated operating sequence of a VCB is O-0.3ms-CO-15s-CO (type1). It is possible to insert a delay into the CO sequence, so the first two switching operations (insert reactor, remove reactor) could be accomplished by one switch. But the last state of the switch is O, so the reactor will remain switched into the line. If more OC sequences are needed, more parallel VCBs are necessary. For n OC sequences n VCBs are needed. A VCB with a special operating mechanism which is assumed to be able to switch every second is also investigated. The following operating sequence then could be attainable: O-1s-C-1s-O-1s-C (type2). One VCB of this kind is too slow to damp the power oscillation, but with the configuration of Figure 2b, it is possible.

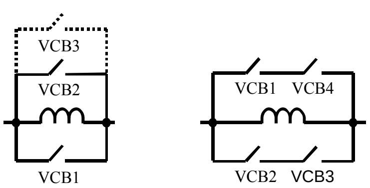


Figure 2: a) type1 configuration b) type2 configuration.

It should be mentioned, that VCBs have an on- and off-delay time which is the time from closing or opening command to closed or opened contacts. In case of this investigation, the on-delay time is set to a constant value of 70ms and the off-delay time to 50ms. Table 1 shows the switching status of the type2 configuration, in order to insert and to remove the reactor into the controlled line. In the first row is given the status of the reactor.

Table 1: Switching status of type2-Configuration.

Status	0	1	0	1	0	1	0	1	0
VCB1	C	O	O	O	C	C	C	C	C
VCB2	O	O	C	C	C	C	C	O	O
VCB3	C	C	C	O	O	O	C	C	C
VCB4	C	C	C	C	C	O	O	O	C

1: Reactor inserted / 0: reactor short-circuited

The minimum time to the next status change of each VCB is 1.5s as three cycles have to pass by. The final status after every damping process is the short-circuited reactor (status 0).

2.4. **First Controller design**

In this investigation a simplified controller for power oscillation damping is used to find the optimal instant to insert the reactor. The controller itself is not part of this investigation; only an initial approach should be mentioned at this point. The total transmitted active power is assumed to be constant before and after the fault. Therefore the turbine power of the generator is set to a constant value. The terminal voltages at the synchronous generator and at the infinite bus are also assumed to be constant. The idea is to measure only the active power in the controlled line and then to calculate the presumably active line power after the fault by knowledge of the surrounding transmission system, the line impedances and the fault duration. The controller calculates in every line active power maximum the expected value if the reactor was inserted and then removed again in the line power minimum. If the calculated value is lower than the calculated steady state active power it immediately gives a command to insert the reactor. In the following line power minimum, a command to short-circuit the reactor is given. The line power is assumed to be ideally measured with no noise on the signal.

2.5. **Protection of the reactor**

In case of short-circuit in the electrical network and inserted reactor step, the opened VCBs are stressed with high overvoltages as the high current flowing through the reactor produces a high voltage drop. Hence a protective circuit has to be installed. A MOV switched into parallel to the reactor and a high-voltage circuit breaker can serve for this purpose. The MOV protects the device while the short-circuit current flows. The advantage is that the device is in operation directly after fault clearing. Only for thermal overloading of the MOV or major faults, the high voltage circuit breaker can bypass the device. Slightly different is the situation if the reactor is short-circuited by the VCBs so the line current flows through them. That should be no problem, because the VCBs can handle short-circuit currents up to 40kA [1].

3. SIMULATION OF THE ELECTRIC NETWORK

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

3.1. Electric network configuration

An electric network with a line-line voltage of 400kV and a system frequency of 60Hz is investigated in this study. It is a single-machine infinite bus system with three parallel transmission lines. Line 1 and 2 have the same length of $l = 100$km. Line 3 represents a parallel corridor with a length of $l = 150$km. The transmission lines are represented by a distributed RLC traveling wave model which is offered in PSCAD [3]. The used tower model is a Donau pylon [2]. PSCAD can calculate the corresponding PI-section model parameter: The line impedance equals $X_{\mathrm{Line}} = 0.3\Omega/\mathrm{km}$. The synchronous generator symbol represents 4 machines with 700MVA each. The rated voltage of every generator is 21kV and the inertia constant is $H = 3$s. The inertia constant has a huge impact on the power oscillation frequency as well as the chosen voltage level, impedance of the transmission system, and stationary load angle before the fault [5]. The parameters of the investigated case lead to a power oscillation frequency of about 1Hz. The infinite Bus symbol represents a strong node with a short-circuit power of 100GVA. Its line to line voltage level is 400kV. The X/R-Ratio of the source impedance is 10. Therefore the impedance of this supply is $X_q = 1.6\Omega \cdot e^{j\cdot 84.24°}$. The phase shift of this voltage source is set to zero. The tapped reactor is inserted at station A as can be seen in Figure 3.

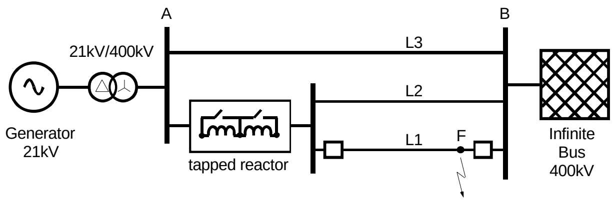


Figure 3: Configuration of the electric network.

Two different load flow conditions are used to investigate the electrical stress on the VCBs. One is for power oscillation damping and the other one is for load displacement.

a) Power oscillation damping (POD)

The generator transmits 2300MW into the grid in the first scenario (scene1) over three parallel lines. Line 1 and 2 are loaded by 842MW each and line 3 by 572MW. Then a three phase fault with connection to ground occurs at point F and line 1 is disconnected after 80ms. Only one step of the tapped reactor is investigated. The other one is short-circuited all the time. Further steps of the reactor in case of POD will be used when the POD controller is optimized.

b) Load displacement

In the second scenario line 1 is not active and the generator transmits an active power of 1862MW into the grid. Line 2 is loaded by 1107MW and line 3 by 740MW. The tapped reactor has two steps whereas every step has an impedance of $X_{Step} = 3.77\Omega$. A stray capacitance of the reactor is considered in this case. It is added between the both inductances to ground.

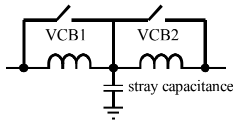


Figure 4: Stray capacitance of the reactor.

The stray capacitances at both terminals which are directly connected to the lines are neglected because they are very small compared to the line capacitances.

3.2. VCB configuration

The VCB model used in this investigation is from [6] where it was used to simulate a vacuum contactor. However it can be used for modeling a VCB with new parameters, which are given in Table 2. The maximum voltage of the considered VCB is taken from data sheet [1]. The arc voltage is set to zero. It is only required if energy conversion in the tube has to be considered. The chopping current is set to a constant value of 5A differing from [6]: The simulation results are then comparable and it represents the worst case scenario, as typical values of VCBs lie in the range of 2A − 5A [7], [8]. The value of the dielectric recovery slope is estimated.

Table 2: Setup parameters for VCB Model.

Parameter	Value	
maximum voltage	95	kV
Resistance (open)	1000e6	Ω
Resistance (closed)	80e-6	Ω
slope of dielectric strength	5	kV/µs
slope of dielectric recovery	7	kV/ms

PSCAD calculates the solutions of the differential equations of the electrical system with a constant step size. A maximum step size of 20µs is necessary in order to incorporate the characteristics of the VCB model. For the detailed curves and transient recovery voltages (TRVs) across the VCBs while they are opening, the step size was reduced to 4µs in the power oscillation case and to 1µs in the load displacement case.

4. SIMULATION RESULTS

4.1. Power oscillation damping

1.1.1. Influence of different reactor impedances on damping

Figure 5 shows the damping of the power oscillation for different impedances of the inserted reactor. The peak-peak amplitude of the oscillation gets lower than 5% of the new steady state line power after 24s in the regarded case without additional damping. If the damping reactor has a small inductance of 5mH the additional damping is not sufficient and the VCBs have to be switched very often. The oscillation needs at least 10s to get into the 5% range. If the impedance is too high (30mH) the amplitude of the oscillation has to be very high so that an insertion of the reactor is possible and will not lead to instability. The remaining oscillation has also a comparatively high amplitude in the regarded case after the reactor was inserted three times. It takes 13.7s so that the power oscillation reaches the 5% range. An enhanced operative range is achievable with a smaller inductance. An inductance of 20mH seems to be adequate, which is nearly 25% of the line inductance. The 5% range of the power oscillation is reached after just 5.4s. A compromise between high damping and broader operating range can be achieved if a tapped reactor with different values of impedances is used. The POD controller can than decide which one to insert depending on the actual difference between the amplitude of the power oscillation and the steady state power after the disturbance. As mentioned above, the next step will be optimizing the controller.

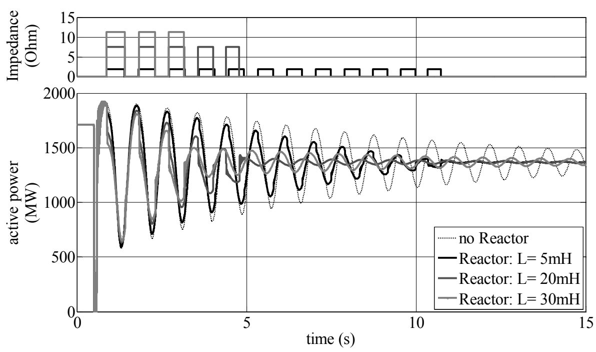


Figure 5: Damping of the power oscillation with different impedances

1.1.2. Calculation of the resulting power after inserting the reactor step into the line.

Every time the power oscillation reaches a positive maximum value, the controller calculates the power which would result if the reactor step was inserted into the line and removed again in the power minimum. This value is compared to the calculated steady state active power after the disturbance. If it is smaller, the controller gives a command to insert the reactor immediately. The process of power calculation in every power maximum can be seen in Figure 6. The inductance of the reactor is set to 15mH in this case. At $t = 0.53$s the calculated power is slightly higher than the calculated steady state power of the line, so no further insertion command is given.

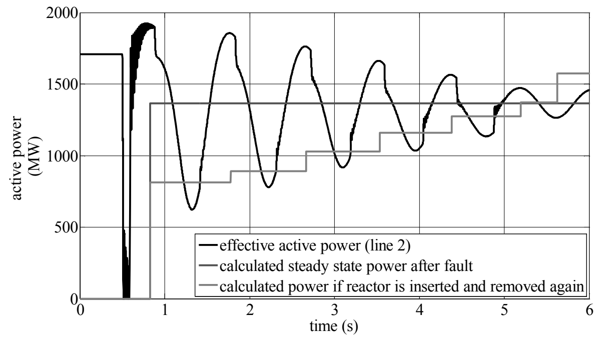


Figure 6: calculation of the resulting power

1.1.3. Currents and Voltages of VCBs and Reactor

A current of 2.49kA flows through the two VCBs which are short-circuiting the reactor in steady state operation before the fault occurs, see Figure 2b. If one of them is opened, the current goes on flowing through the reactor. This can be seen in the lowest graph of Figure 7. Every time the reactor is short-circuited again, a DC-Trapped current occurs, which decays with a time constant of $\tau = R_{reactor}/L_{Reactor} = 0.5$s. The reactors inductance is in this case set to a high value (30mH). When the respective VCB opens the first time, the maximum voltage across it reaches a value of 55.5kV but the maximum voltage of the VCB is not exceeded.

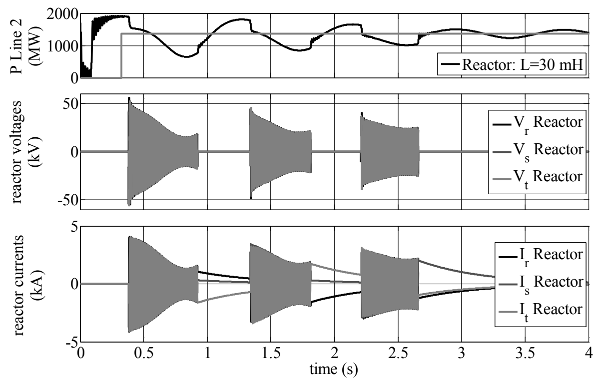


Figure 7: currents and voltages of the reactor.

Figure 8 shows the detailed TRV in phase t of one VCB, if the reactor is inserted into the line the first time as well as the dielectric recovery of the gap.

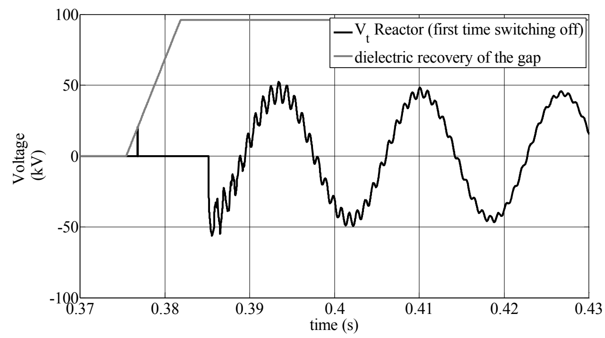


Figure 8: Detailed TRV across the opening VCB.

At $t = 0.376$s the contacts are starting to open and the recovery voltage is increasing. As current through VCB falls below the value of chopping current, it is interrupted immediately and a (TRV) occurs. The first peak at $t = 0.377$s is an unsuccessful interruption. The TRV exceeds the dielectric strength of the opening gap and a restrike occurs. Current goes on flowing until next zero crossing and is then successfully interrupted. The peak value and frequency of the oscillation of the TRV depend on the inductance and the line capacitances to ground. The TRV slope is in this case $0.45\text{kV}/\mu\text{s}$ and within the range of VCB parameter. The frequency of the TRV is about 1.11kHz. It should be mentioned, that the moment of short-circuit does not change the maximum amplitude of the TRV but indirectly it changes the starting position of the recovery voltage ramp and therefore the height of the first small peak. The TRV peak value is affected by the short-circuit duration: The amplitude of power oscillation increases and so does the current through the controlled line. The maximum inductance value of a reactor has to be adapted to the maximum current which can occur during a power oscillation because it affects the voltage drop across the reactor. This depends on the regarded electrical network.

The currents through the reactor, VCB1 and VCB2 in type2 configuration are shown in Figure 9. The DC-part of the reactor current overlies the line current, both flowing through the respective VCB if it is closed. This can be seen in the lower graph at $t = 0.93$s and leads to a very short period, where the VCB current may have no zero crossings. An opening command in this period could lead to destruction of the VCB because of thermal overheating. It needs a zero crossing in order to successfully interrupt the current. Anyhow, the DC part has enough time to decay before the next switching command so no problem should be expected.

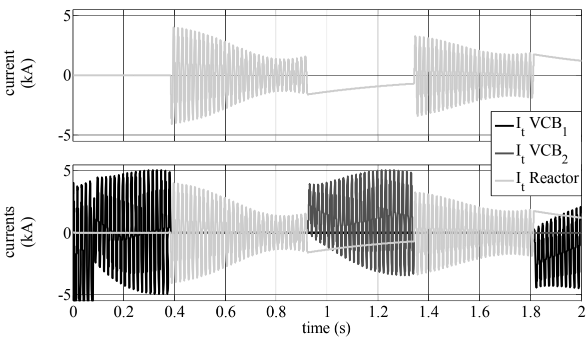
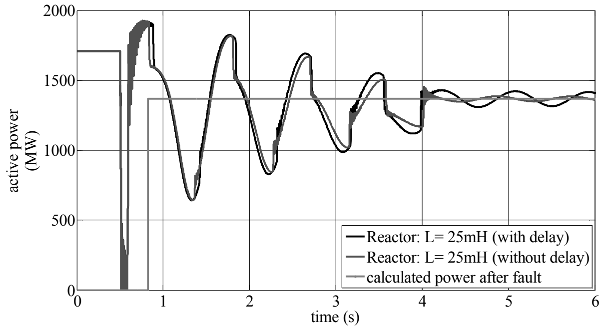


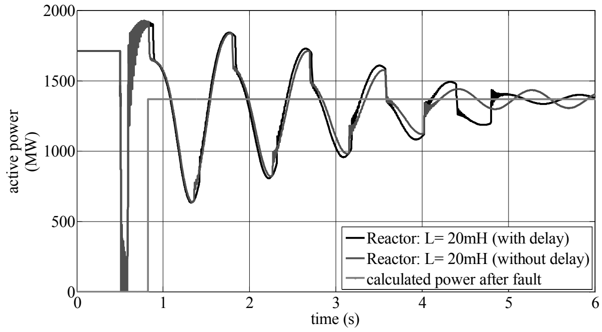
Figure 9: VCB and reactor currents in phase t.

1.1.4. Influence of on- and off-delay times

The on- and off-delay times of VCBs were already mentioned in section 2.3. The impact on the damping process is assessed in Figure 10. The upper graph shows the damping of the power oscillation with an inductance of $L_{Reactor} = 25\text{mH}$ and the second with $L_{Reactor} = 20\text{mH}$. In the first case, the delay times have a negative effect, see Figure 10a. The amplitude of the remaining oscillation with delay times included is 4.5% referred to the steady state line power and with delay times neglected it is 1.5%. In the second case, it is similar, but the additional insertion of the reactor at $t = 4.4$s reduces the remaining amplitude of the power oscillation.



a) $L_{Reactor} = 25\text{mH}$



b) $L_{Reactor} = 20\text{mH}$

Figure 10: on-/ off-delay time: impact on damping.

Summing up the negative effects of the delay times can be balanced by an adequate rating of the reactor and additional insertion of it.

4.2. **Load displacement**

The second scenario for load displacement as described in section 3.1 is used in the following. The Insertion of the reactor steps leads to a power oscillation as can be seen in Figure 11. The new active power after inserting the first step of the reactor is 1056MW (minus 4.6%) and after inserting the second step it is 1008MW (minus 8.9%). The worst moment of inserting a second step after the first one was inserted is at the power oscillation minimum. This case is presented in the lower graph. If it is inserted in the power maximum, the existing oscillation is nearly eliminated.

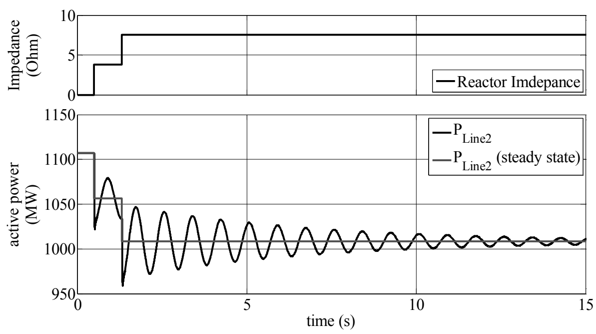


Figure 11: Inserting the reactor steps in line 2.

If every reactor step is bypassed and one step is going to be inserted, the TRV peak at the opening VCB mainly is affected by the line capacitances and the inductance of the switched step. As the line capacitances are very high in comparison with the stray capacitances of the reactor step the VCB parameters are not exceeded. But if a further step is inserted the stray capacitance to ground between both affected steps becomes active and can lead to very high TRV peaks with high slopes. This worst case scenario is used for the following detailed consideration. The stray capacitance is set to 50pF. The upper graph of Figure 12 shows the unsuccessful opening of a VCB in order to insert the second reactor step. Although the maximum voltage of the VCB is not exceeded, a current interruption is impossible because the slope of the TRV is about 25kV/μs, much higher than what the VCB is able to handle. This leads to restrikes in the VCB and current cannot be successfully interrupted.

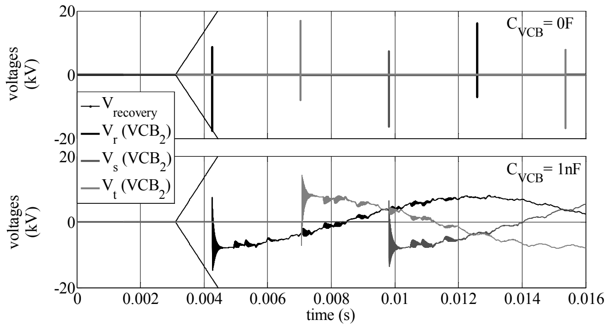


Figure 12: TRV without/with a capacitor across VCB.

A possibility to avoid transients at the VCBs with high amplitudes and large slopes is to connect a capacitor with higher value compared to the stray capacitance parallel to it. This effect can be seen in the lower graph. The capacitance across the VCB was in this case set to 1nF and the situation is enhanced considerably. The slope is 3.85kV/μs and the amplitude is 14.3kV both within the VCB parameters. The frequency of the oscillation is approximately 68kHz. No additional capacitor is necessary if the stray capacitance has a minimum value of 100pF. In real configuration, the stray capacitance of the reactor has to be well estimated. If problems are expected, an additional parallel capacitor should be provided for the VCB due to protective reasons.

5. CONCLUSIONS

This paper shows that a mechanically switched tapped reactor can perform various tasks like load displacement and POD in a special configuration. The stray capacitance of the reactor has a big influence on the TRV in load displacement case if a tapped reactor with different steps is used and one step is already inserted into the line. High TRV peaks and slopes can occur across the opening VCB. If this leads to an exceeding of the VCB parameters, a capacitor connected in parallel to the respective reactor step improves the situation considerably.

Additional damping can be delivered to stable electrical power systems which are weakly damped. The resulting electrical stress on the components like the reactor and the VCBs while switching operations occur does not exceed the parameter of the used VCBs. In this investigation it was found out that a reactor impedance of approximately 7Ω leads to an optimal damping process because it delivers sufficient damping and only few switching operations are necessary. If a higher damping is needed, the taps of the reactor can be equipped with different impedances. The POD controller can then decide which inserted value would result in the best damping. Further investigations and optimization of the POD controller is necessary and will be accomplished in order to guarantee a satisfactory operation in different network configurations.

6. REFERENCES

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