Voltage Stability with Mechanically Switched Capacitors using Vacuum Circuit Breakers in the High-Voltage Grid

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***Abstract*-This Paper shows one of the possibilities, where Vacuum Circuit Breakers (VCBs) can be utilized in flexible AC transmission systems in the High-Voltage Grid. Although VCB can only switch at a low repetition rate in comparison to electronic switching devices, it is justifiable to use them, if the main focus is lying on a cost-effective device with a selected working operational range. VCBs are used in this case as switching elements as they can be switched more often without maintenance compared to other circuit breakers. In this paper mechanically switched capacitors, which are connected to a node in the h.v. system in order to enhance the voltage quality at this node and to avoid a voltage collapse are investigated. As VCBs are mainly available in the medium voltage range a transformer will be used to connect the mechanically switched capacitors to the h.v. system. Based on a simulation it could be shown, that the mechanically switched capacitors using VCBs can stabilize the voltage of the node in case of disturbances in the power system like faults. The electrical stress on the VCBs and on the capacitors for different simulation cases is assessed. The simulation is performed with PSCAD.**

I. INTRODUCTION

Usually Static Var Compensators (SVCs) are used to stabilize the voltage at a load node in the power system and to improve the power factor of the connected load. A new idea is to create a cost-effective device which is mechanically switched by VCBs and to investigate its possibilities in an electric energy system. In this case a mechanically switched capacitor (MSC) for medium voltage which is connected to the h.v. system by a transformer is investigated. A special point of interest in this paper is the question if those MSCs can avoid voltage instability when the load consists of several induction machines:

If the voltage in one or more phases at the load node breaks down because of faults or line outages, the induction machines decelerate which leads to a higher consumption of reactive power. This in turn leads to a further reduction of the voltage at the node and so on. If the duration of the disturbance is too long, the mechanical shaft torque of the machines gets higher than the electrical torque thus making it impossible to recover rated speed [1]. The voltage instability then occurs in form of a progressive gradual fall of the voltage at the respective node [2]. A possibility to break this loop is to offer capacitive reactive power directly at the involved node in order to boost the voltage. The machines can reaccelerate and obtain their rated speed.

The used VCBs and the design of the MSCs is described in the following section. Afterwards the electrical circuit used for the simulation is presented. Finally the electrical stress on the VCBs and capacitors is assessed for different scenarios like avoiding a voltage collapse after a disturbance in the h.v. system and the further steps are discussed.

II. SYSTEM DESIGN

A. Vacuum Circuit Breakers

VCBs are mainly available in the medium voltage range [3]. They are ideally suitable for capacitor switching, because vacuum has the fastest recovery strength after arc interruption at current zero [4]. This is important, as the voltage across the breaker rises to the double value of the amplitude of the steady state voltage while disconnecting a capacitor from a voltage source within half a period of power frequency. The VCBs used in this investigation can handle capacitive currents up to 70 % of their rated current which is $I_r = 2.5$ kA [5]. The maximum current amplitude in case of closing a capacitive circuit should be limited to 10 kA for the used VCB [5]. But according to the standards [6] every VBC has to withstand an inrush current with an amplitude of 20 kA at a maximum frequency of 4250 Hz while switching a capacitor. This value is taken as maximum rating in this investigation. The rated short-duration power-frequency withstand voltage of the used VCB is 96 kV. This value is used as the maximum voltage capability of the VCB model. The tubes need maintenance after 30.000 switching operations, the mechanical parts after 10.000 switching operations [7]. It should be mentioned, that VCBs have an on- and off-delay time. The on-delay time is the time from closing command to closed contacts and the off-delay time from opening command to the start of movement of the contacts. In case of this investigation, the on-delay time is set to a constant value of 70 ms and the off-delay time to 45 ms according to [7].

B. Mechanically Switched Capacitor

The purpose is to achieve a capacitor bank with a preferably high reactive power. In this investigation the deliverable capacitive reactive power is chosen to be

300 Mvar. In order to have a grading, the total capacitance is split into three particular parts with the same ratings. A transformer is used to connect the capacitors to the h.v. system. The low voltage side of the transformer is set to 36 kV, which is the rated voltage of the used VCBs.

Two types of capacitor switching are possible: Single bank switching and back to back switching. In case of single bank switching only one capacitor is connected to the grid. The inrush current is mainly affected by the inductances on the path from the source to the capacitor. In case of back to back switching, where one capacitor is already connected to the grid, and another one is connected afterwards, the inrush currents are mainly influenced by the inductances in the path from the first to the second capacitor. Hence, current limiting reactors should be designated in order to reduce the currents in case of back to back switching. It should be mentioned that both the transformer and the current limiting reactors consume a part of the capacitive reactive power. This is incorporated when the capacitor ratings are assigned. A load flow calculation resulted in a value of C = 172 μF for each capacitor. A star connection with ungrounded neutral point is used.

The capacitive reactive power at 36 kV is 84 Mvar for one three phase system. It depends on the actual voltage on the low voltage side of the transformer and will increase because of the capacitive voltage rise the more capacitors are connected. The effect of capacitive voltage rise is illustrated in Fig. 1 where a simplified equivalent circuit of a transformer with a capacitive load C is shown together with the associated phasor diagram. If all capacitors of the bank are connected, and a voltage of 400 kV is achieved on the h.v.-side of the transformer, the low side voltage is nearly 41 kV. Regarding the capacitive voltage rise and less the above mentioned reactive power consumption, the calculated reactive power of one connected MSC is 93 Mvar, of two connected MSCs it is 195 Mvar and if all three MSCs are connected it is the design point of approximately 300 Mvar. The steady state current in one phase is 1.5 kA (1 MSC), 1.56 kA (2 MSCs) and 1.63 kA (3 MSCs). This is within the specifications of the used VCB.

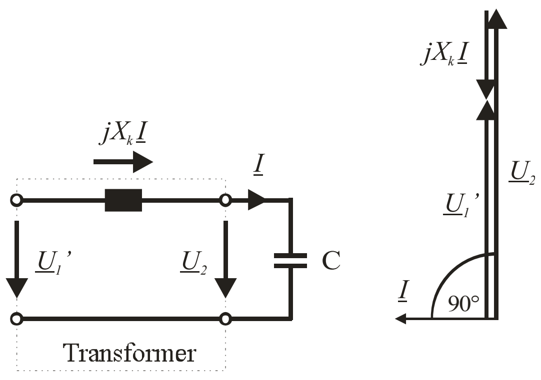

Fig. 1. Capacitive voltage rise at a transformer [8]

The inductance of the current limiting reactor is designed in such a way that the frequency of the resonant circuit is the fourth harmonic: Choosing a smaller resonant frequency would decrease the expected currents but it is not advisable in order to retain a safety margin to the power system frequency. Theoretically, the maximum voltage amplitude across the switching element is 2.5 times the amplitude of the steady state system voltage when ungrounded capacitors are used and can be calculated by the following equation [9].

$$U_{VCB\_\max} = 2.5 \cdot \frac{\sqrt{2}}{\sqrt{3}} \cdot U_{MSC\_rms} \tag{1}$$

Regarding the capacitive voltage rise and assuming that all three MSCs are connected, a maximum voltage amplitude of $41\text{ kV} \cdot \sqrt{2} / \sqrt{3} \cdot 2.5 \approx 83.7\text{ kV}$ is expected which is within the rated short-duration power-frequency withstand voltage.

III. Simulation Model

The simulation tool used is PSCAD, which is a graphical interface to the EMTDC software [10].

A. Electric network configuration

An electric network with a line-line voltage of 400 kV and a system frequency of 60 Hz is investigated in this study. Fig. 2 shows the electrical configuration. A source G feeds a load over a transmission line A-B. The source is a strong node with a short-circuit power of 100 GVA. The X/R-Ratio of the source impedance is 10. The line has a length of 120 km. It is represented by a distributed RLC traveling wave model which is offered in PSCAD [10]. The used tower model is a Donau pylon [9]. PSCAD can calculate the corresponding PI-section model parameter: The line impedance equals 0.3 Ω/km.

The load content is a combination of a PQ Load model and a contingent of induction machines. The load consumes all together an active power of nearly 1000 MW. The induction machine symbol represents 300 machines with a rating of approximately 2.3 MVA each operated as motors. The rated voltage of the machines is 13.8 kV so a transformer connects them to the h.v. system.

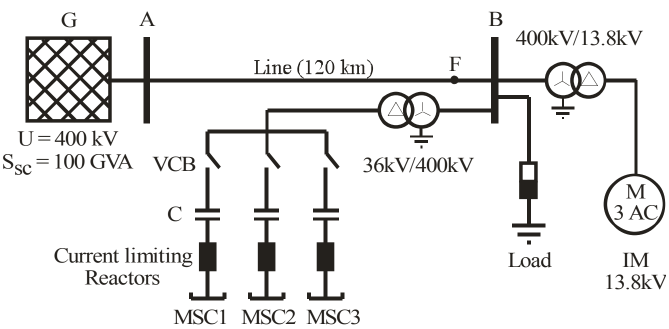

Fig. 2. Configuration of the electric network

The transformer has a rated apparent power of 1000 MVA. The inertia constant of the induction machines is set to H=0.75 s. It has been calculated from the data of an induction machine with an active power of 1.9 MW [11] and has a huge impact on the loss of speed of the machines in case of voltage drops at their terminals. The mechanical shaft load is assumed to have a linear dependency on the speed. Other dependencies can be chosen by changing the exponent of the motor mechanical torque from 1 to zero (conveyor system) or 2 (fans or pumps). The higher the exponent, the more stable behave the machines in case of voltage drops.

Two scenarios are investigated:

Scenario a) The load consists only of the PQ Load. The PQ load model has a power factor of 0.9. A constant current is assumed for the active power and a constant impedance for the reactive power. This represents a typical load characteristic [12].

Scenario b) The load consists of 60 % induction machines and additionally 40 % of the load described above. It is a typical contingent of induction machines in electric power systems [12].

For the simulation the load can be increased in 3 steps by 12 % each in scenario a) starting from an operating condition just requiring no compensation. Increasing the load by 12 % leads to a voltage drop of 8 kV at the load node, so the maximum voltage drop that can be achieved is 24 kV.

The three MSCs are connected in parallel to the load behind a transformer with a rated power of 300 MVA. One MSC increases the voltage by 8 kV. The low voltage side of the transformer is in delta connection.

An additional bus inductivity of 20 μH is incorporated. The current limiting reactors have a quality factor of 180, so a resistance is series connected to the inductances. The losses of the capacitors are assumend to be 0.15 W/kvar [13], so a resistor with approximately 103 kΩ is switched parallel to each. This leads to a discharging time constant of $\tau = R \cdot C \approx 18$ s .

B. VCB configuration

The VCB model used in this investigation has been described in [14] 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 I.

TABLE I
SETUP PARAMETERS FOR VCB MODEL

Parameter	Value	
maximum voltage	96	kV
Resistance (open)	1000e6	Ω
Resistance (closed)	80e-6	Ω
slope of dielectric strength	5	kV/μs
slope of dielectric recovery	15	kV/ms

The maximum voltage of the considered VCB is taken from data sheet [7]. The arc voltage is within the range of 20 V to 30 V [3] and can be neglected in case of this investigation. 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 [14]: The simulation results are then comparable and it represents the worst case scenario, as typical values of VCBs lie in the range of 2 A – 5 A [3], [5]. The value of the dielectric recovery slope is estimated. A small capacitor across the VCB contacts is incorporated in every phase with a value of 10 pF.

PSCAD calculates the differential equation solutions of the electrical system with a constant step size. A maximum step size of 20 μs 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 or closing, the step size is reduced to 5 μs in all simulations.

IV. SIMULATION RESULTS

The elelctrical stress on the VCBs is a high transient recovery voltage (TRV) in case of disconnecting the capacitor from the grid and a high current in case of connecting it. The first part of this section shows the simulation result of scenario a) while disconnecting the MSCs and connecting them and the second part shows the results of scenario b).

A. Scenario a)

1. Electrical stress – Voltages

The load is set to 112 % and the simulation runs until steady state conditions are attained. A MSC is inserted thus increasing the voltage to 400 kV. A 12 % load reduction causes a voltage increase to approximately 408 kV. The MSC is finally switched off whereas the disconnecting time is varied over one period of power system frequency. The maximum occurring TRV amplitude is recorded.

Fig. 3 shows the voltages across the VCB and the capacitor C and the currents through both. The effective MSC voltage before switching it off is 38.1 kV which is higher than 36 kV and caused by the load rejection. The maximum TRV voltage amplitude across the VCB is 74.7 kV in the first interrupted phase which is slightly smaller than calculated by (1).

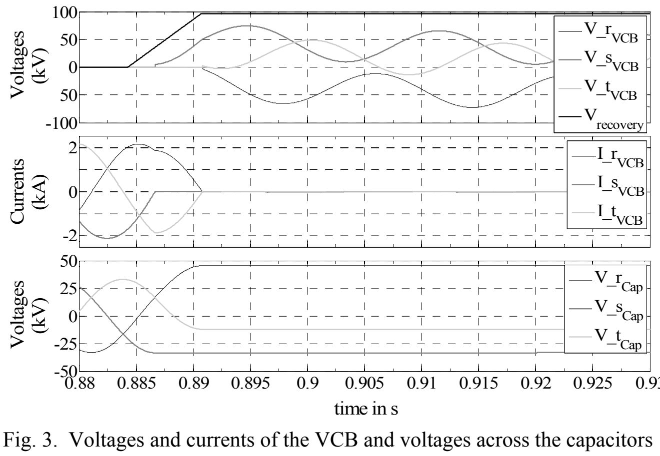

Fig. 3. Voltages and currents of the VCB and voltages across the capacitors

This is because of the additional elements like the resistive parts of the current limiting reactors and the bus inductances.

The recovery voltage of the VCB gap is shown in the upper graph, too. The highest voltage across the capacitors occurs in phase r and is 45.6 kV. It is theoretically 1.5 times the amplitude of the MSC voltage [9]. Although the TRV obtains a very high value, it is within the specification of the used VCB. Its slope is smaller than the slope of the dielectric recovery voltage, so a current interruption is possible without problems.

The same sequence is now repeated with a load of 124 %. Two MSCs have to be connected to the node in order to keep the voltage at 400 kV. Then 12 % of the load is shed after reaching steady state conditions. Finally one MSC is disconnected from the node. This time, the MSC voltage has a higher value because of the load rejection on the one hand and the capacitive voltage rise on the other hand. It is 39.7 kV before disconnecting the MSC and 37.4 kV afterwards. The amplitude of the TRV in the first interrupting phase is 79.2 kV and the maximum capacitor voltage in phase r is 47.5 kV. The same sequence repeated, but with all three MSCs in service at the beginning, the maximum voltage in the first interrupting phase is 82.6 kV and the maximum voltage of the capacitors is 49.3 kV in phase s. The MSC voltage before disconnecting one MSC is in this case 41.6 kV and 39 kV afterwards. Regarding these three cases, the capacitive voltage rise results in high TRV values in the first interrupting phase, but all values are within the VCB specifications.

The next investigated case starts with a load of 136 % and all three MSCs are in service. After reaching steady state conditions a large load reduction to 100 % occurs, leading to a high voltage of 43.4 kV at the MSC terminal. All three MSCs have to be disconnected directly in order to avoid an overvoltage at the h.v. node. The earliest moment of disconnecting them is set to 70 ms. This time composes 45 ms time delay of the VCBs and 25 ms for detecting the overvoltage. The first MSC is switched off in the voltage maximum and the switching moment of the other MSCs is varied within a period of power system frequency.

The maximum voltage is detected, when both of them are disconnected 4 ms later. It is 86.8 kV in the first disconnected MSC and 83.9 kV in the others. The voltage of the first MSC is very close to 96 kV given in Table I. In order to maintain a higher safety margin, it is possible to reduce the rated voltage level of the MSCs or to use an grounded capacitor bank: Then the theoretical maximum voltage across the VCBs would be two times the amplitude of the MSC terminal voltage [9]. The maximum voltage of the capacitors in the first MSC is 52.3 kV in phase t. The voltages across the capacitors decrease with a time constant of 18 s calculated in section III.A. In [15] is arrogated, that the capacitor voltage should be lower than 50 V after 5 min. Assuming an initial voltage of 50 kV, it takes about 2 min, until 50 V are obtained so it is within the requirement.

A worst case scenario was found out to be a restrike in one phase of the VCB, which is disconnecting a MSC, when the voltage across the VCB has reached the maximum. If additionally the emerging current is interrupted in the first zero crossing, the voltages across the capacitors and the VCB can reach very high values. This case is presented in different literatures [16], [17] and surge arresters are proposed to avoid it. Of course there are several other possibilities to exceed the VCB voltage limit, for example, if one MSC is inserted and disconnected immediately during the transient phenomenon while other MSCs are in service. But all simulations showed that the transient phenomenon abated sufficiently approximately 2 s after MSC switching. A controller has to make sure, that a congruent time delay is considered after switching processes.

2. Electrical stress – Currents

At first the currents during single bank switching are investigated and afterwards the currents during back to back switching.

The simulation is started with 100 % load followed by an increase of 12 %. The voltage drops to 392 kV at the load node. Now one MSC is connected and the moment of switching varied over one period of power system frequency. The maximum current in the VCB is recorded but only while the VCB is closing: with closed contacts, the VCB is able to handle currents up to 100 kA for a few seconds [7]. Fig. 4 shows the VCB currents and voltages. The inrush current gets maximal, if the respective capacitor of the MSC is connected in the voltage maximum. In this case, phase t has a voltage maximum, while the capacitor is connected so the current in phase t reaches its maximum value of value of 5.3 kA within the closing process. The closing process can be seen in the upper graph, while the recovery voltage of the VCB decreases to zero. The maximum current after the finished closing process is 7.4 kA. The current amplitude in this case is mainly influenced by the voltage amplitude, the inductances in the source path (source, line, transformer, current limiting reactor) and the capacitance of the MSC. Although the resonant circuit of current limiting reactor and the capacitance is designed to the fourth harmonic, the frequency of the current oscillation is 186 Hz, which is considerably lower. This is due to the inductance of the source path in case of single bank switching.

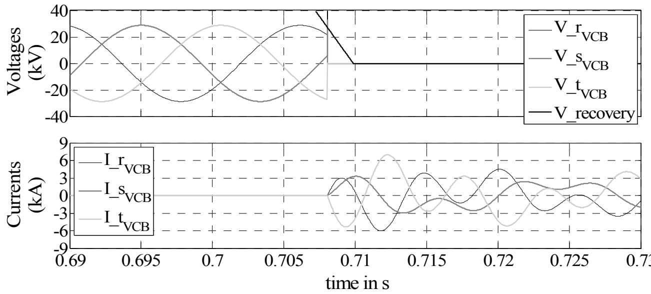

Fig. 4. Voltages and currents of the VCB while connecting a MSC

The ohmic part of the load causes a fast decrease of the higher harmonics in the current. The maximum capacitor voltage is in this case 53 kV. The MSC voltage before connecting the MSC is 35.1 kV and 37.4 kV afterwards.

Now the same situation is investigated, but this time, the connected MSC has pre-charged capacitors. That means, it has been switched off for some seconds before and for some reasons has to be reinserted. Fig. 5 shows the voltages and currents in this case. In the lower graph can be seen the pre-charge voltage level. The capacitor, which has the highest voltage difference to the system voltage while being connected, generates the highest current amplitude. This can be seen in phase t. The voltage level of the capacitor is 44.3 kV and the system voltage is -73 kV. This leads to a maximum current amplitude of 14.6 kA while the VCB is closing. The capacitor voltages attain high values because of the high currents, for example -86.3 kV in phase s.

As the above mentioned case with a pre-charged MSC results in much higher currents, this case is applied for the investigation of back to back switching. The simulation starts with all MSCs in service, because the load is 136 %. One MSC is disconnected and shortly thereafter it is inserted again. This case is illustrated in Fig. 6. The maximum current is 16.6 kA in phase s, which is relatively close to limit given in [6]. The currents in the other MSCs are reaching values up to 11.1 kA, but that is no problem as the VCBs are closed. The maximum capacitor voltage is -97 kV in phase s. The MSC voltage before inserting is 38.1 kV and 40.7 kV afterwards. It can be seen in phase r in the upper graph of Fig. 6, that there is a successful current interruption of the high-frequency current at 3.08 s. But as the recovery voltage of the VCB decreases, it is exceeded by the emerging voltage shortly afterwards. Then the current in phase r starts to flow again, which can be seen in the middle graph at t = 3.082 s.

The currents are now mainly influenced by the inductances between the MSCs and not by the inductances in the source path as in single bank switching. Now the frequency of the higher harmonic current is 240 Hz as expected. The current oscillations are only damped by the losses of the capacitors and the limiting reactors in this case which takes longer than during single bank switching.

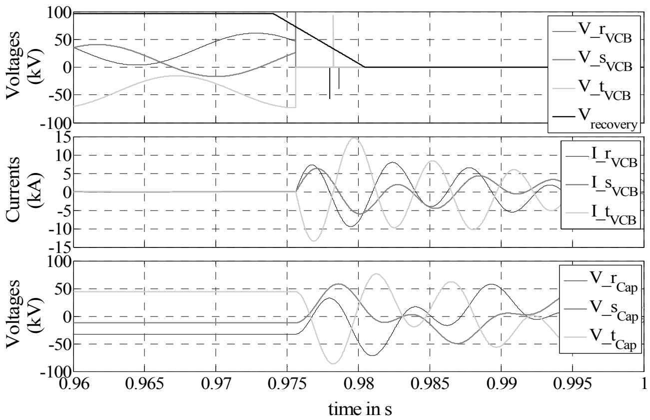

Fig. 5. Voltages and currents while connecting a pre-charged MSC

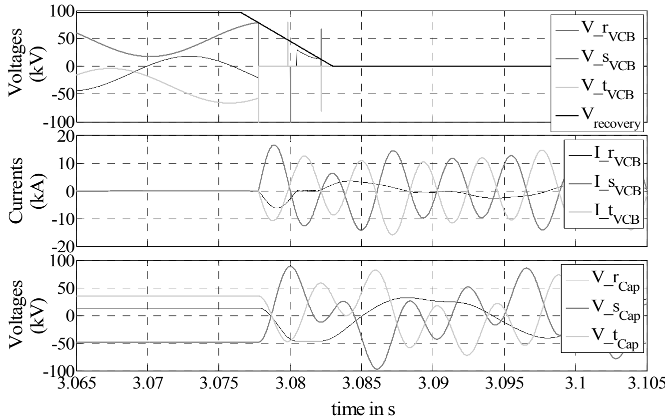

Fig. 6. Voltages and currents while connecting a pre-charged MSC

The current amplitudes do not increase very much if one or two MSCs are already in service while another pre-charged MSC is connected. This is because the inductances of the source path and the inductance of the current limiting reactor are within a similar range. It can be seen if the inrush current frequency is regarded. It is 186 Hz for single bank switching and 240 Hz for back to back switching. A slight current rise is determinable mainly because of the capacitive voltage rise, which is increasing, the more MSCs are connected.

B. Scenario b)

Now the results of scenario b) where the load consists of 60 % induction machines are presented.

In the first case, the system is running in steady state. The machines are running with rated speed of 0.98 pu and the active power of the total load is nearly 1000 MW. Then a single phase short-circuit is applied in phase r at the point F (Fig. 2) for 120 ms. It is the maximum fault time, at which the voltage just will stabilize itself even without the MSCs.

Fig. 7 shows the power of the induction machines, the effective voltage on the low voltage side of the transformer (middle graph) and the speed of the machines (lower graph). At 2.5 s the voltage drop during the fault can be seen in the middle graph. After the fault has been cleared, it takes nearly 2.469 s until the rated speed is achieved again.

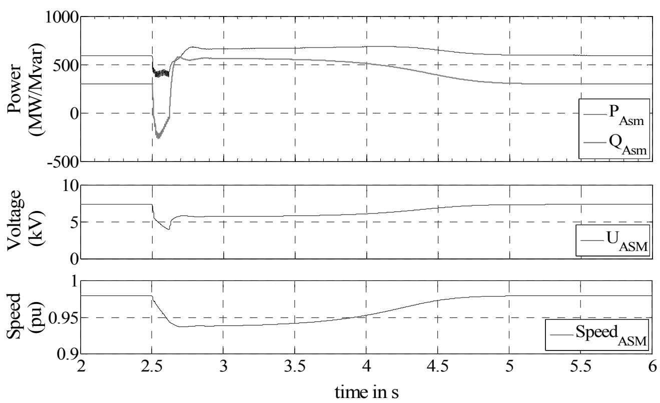

Fig. 7. Fault applied and no MSC in service – voltage and speed

With longer fault duration, the speed of the machines would continue to decrease and so would do the voltage.

Now the same situation is investigated but all MSCs are inserted as early as possible. Regarding the delay time of the VCBs and additional 10 ms for fault detection this is at 2.58 s. The rated speed is achieved considerably earlier which can be seen in the lower graph of Fig. 8. It just takes 0.973 s.

It is not possible for the three MSCs to be inserted at the same moment in reality due to switching delays caused by the differing mechanical properties of the VCBs. There will be rather a short time delay. Fig. 9 shows the amplitudes of the maximum detected currents in the third MSC depending on the switching moments of the second and third MSC. The first MSC is switched at t = 0 s when the voltage in phase r is maximal. The switching moment of the other MSCs is varied over one period of power system frequency. The black line in Fig. 9 marks the same switching moment of MSC 2 and 3. The current amplitudes on the right side of the line are obtained, if the MSC 2 is switched after MSC 3. In other words, the highest current amplitudes will occur in the last switched MSC. Anyhow, all simulations did not show an exceeding of the maximum tolerable currents during the closing process of the VCBs. It should be mentioned, that the graph would just be mirrored around the marked line if the currents of MSC 2 were recorded. This would be different, if the current limiting reactors in each bus were designed to different harmonics.

The same procedure was proceeded in order to obtain the maximum voltages across all included VCBs. The moment of switching all MSCs off was shortly before reaching the rated voltage at the low voltage side of the transformer. The respective graph is shown in Fig. 10. There can be seen the discrete voltage plateaus because the current is always interrupted close to the next zero crossing, when the voltages across the capacitors are at maximum value. The highest voltage during all simulations was 84.5 kV which in fact is quite close to the maximum rating of the used VCB but it does not exceed it. The maximum capacitor voltage is -54.4 kV in the first disconnected MSC. The MSC voltage before disconnecting all MSCs is 42.2 kV and 35.8 kV afterwards.

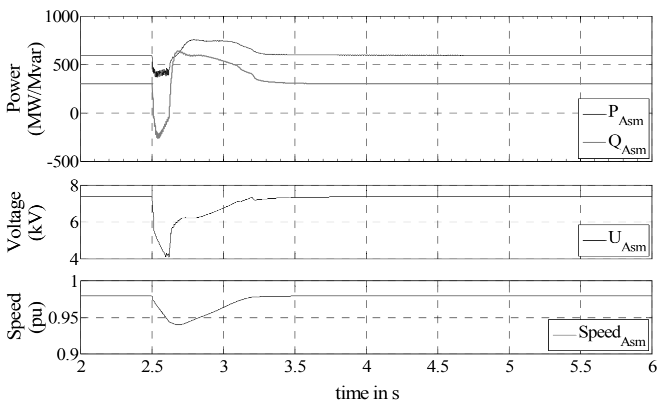

Fig. 8. Fault applied and all MSCs in service – voltage and speed

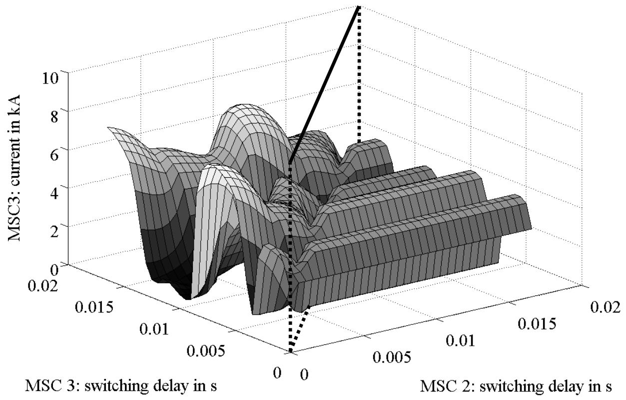

Fig. 9. Current as a function of the delayed switching of MSC 2 and 3

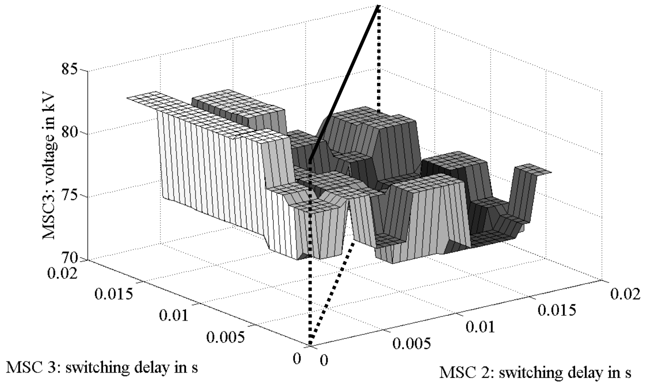

Fig. 10. Voltage as a function of the delayed switching of MSC 2 and 3

By using the MSCs and considering the delay time of the VCBs, the fault time for a single phase fault could be extended to 170 ms without leading to a voltage collapse.

The last simulation was accomplished with a three phase fault with ground connection. This type of fault causes a large voltage drop at the machine terminals: They decelerate faster. The fault can only be successfully restored with the help of the MSCs, if the fault duration is lower than 55 ms. But therefore, they need to be inserted not later than 80 ms after the begin of the fault. Assuming that it needs 30 ms to detect the fault and including the time delay of the VCBs, the fault could not be restored anymore. But it should be pointed out, that the total inertia of the rotating machines is set to 0.75 s and the inertia constant of the mechanical load is not incorporated. Certainly the load will have an inertia constant in reality, too, which leads to an improvement of the situation. It makes the system slightly insusceptible against voltage drops at the machine terminals. Additionally, the mechanical shaft load is assumed to have a linear dependency on the speed. If it is assumed to be quadratic, the three phase fault could last for 75 ms.

V. CONCLUSION

This paper shows a design of a capacitor bank with an apparent power of 300 Mvar. VCBs are used as switching elements instead of electronic devices because the main focus lies on a cost-effective solution. The electrical stress is pointed out for different cases like avoiding a voltage collapse, if the load consists of a large amount of motors in case of a fault. Regarding the specifications of the used VCBs the simulation showed, that their maximum limits have not been exceeded in all simulated cases. In some cases, the voltages across the VCBs got very close to the limits. It could be necessary to reduce the voltage level of the MSCs, if a higher safety margin should be maintained. But this goes along with a reduction of the deliverable capacitive reactive power. Caused by the high frequency currents in case of back to back switching, the capacitor voltages reached high values up to 97 kV. This has to be incorporated for the design. Principally, the MSCs switched by VCBs are able to stabilize the voltage at a node with a high motor load although they have a time delay. The further steps are to implement a controller which avoids wrong or too fast switching processes of the three MSCs and to include a mechanically switched reactor in order to obtain a finer graduation of the provided reactive power. In this case is expected a TRV with a respectively higher slope when the reactor is switched off.

References

[1] T. Van Cutsem and C. Vournas, *Voltage stability of electric power systems*, Kluwer Academic Publishers, USA, 1998, pp. 270-272.

[2] M.Z. El-Sadek and F.N. Abdelbar, “Effects of induction motor load in provoking transient voltage instabilities in power systems”, *Electric Power Systems Research*, 17 (1989), pp. 119–127

[3] H. J. Lippmann, *Schalten im Vakuum – Physik und Technik der Vakuumschalter*, Berlin, Offenbach, VDE-Verlag GmbH, 2003, p. 55, pp. 109-113

[4] Bharat Heavy Electricals Limited, *Handbook of Switchgears*, McGraw-Hill, USA, 2007, pp. 3.26-3.27

[5] Siemens, ”Vakuum-Schalttechnik fuer die Mittelspannung“, Katalog HG 11.01, 2007, p. 14, p. 10

[6] DIN EN 62771-100, High-voltage switchgear and controlgear - Part 100: Alternating current circuit-breakers (IEC 62271-100:2008), German version EN 62271-100:2009, December 2009, p. 68

[7] Siemens, ”Vakuum-Leistungsschalter 3AH2/ 3AH4“, Katalog HG 11.04, 2007, p. 6, p. 33, p. 30

[8] Kuechler, A., *Hochspannungstechnik, Grundlagen – Technologie – Anwendungen,* 3rd ed., Springer Verlag, Berlin, Heidelberg, 2009, p. 355

[9] D. Oeding and B. R. Oswald, *Elektrische Kraftwerke und Netze*, 6th ed., Springer-Verlag, Berlin Heidelberg, New York, 2004, p. 867, p. 755

[10] “PSCAD Electromagnetic Transients – User’s Guide”, Manitoba HVDC Research Centre Inc., 2005, p. 2

[11] Schorch Elektrische Maschinen und Antriebe GmbH, *Drehstrom – Asynchronmotoren fuer die Hochspannung*, Datasheet KA2569X-BH04G, online available at www.schorch.de, downloaded on January 29th 2010

[12] P. Kundur, *Power System Stability and Control*, McGraw-Hill inc., USA, 1994, pp. 272-278

[13] ABB, *ABBACUS Metal Enclosed Capacitor Bank*, Datasheet, 2009, online available at www.abb.de, downloaded on January 19th 2010, p. 4

[14] T. Wenzel, T. Leibfried and D. Retzmann, “Dynamical simulation of a Vacuum Switch with PSCAD”, *16th Power Systems Computation Conference*, Glasgow, Scotland, 2008

[15] IEEE Std 18™-2002, “IEEE Standard for Shunt Power Capacitors”, *Institute of Electrical and Electronics Engineers, Inc.*, USA, October 2002, p. 7

[16] P. G. Slade, *The Vacuum Interrupter: Theory, Design, and Application*, CRC Press, USA, 2008, pp. 363-366

[17] L. Gebhardt and B. Richter, “Surge arrester application of MV-Capacitor banks to mitigate problems of switching restrikes”, *International Conference on Electricity Distribution*, Vienna, May 2007