Transient Recovery Voltages Caused by Capacitor Switching in Wind Power Plants

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***Abstract*—This paper investigates transient recovery voltages across vacuum circuit breakers used for switching mechanically switched shunt capacitor banks in a wind power plant. Simulation case studies are conducted which investigate the transient recovery voltages with the original bank configuration and a number of modified configurations. It is shown that using the original configuration, with inrush current limiting reactor in series with the capacitor, can result in a breaker failure under most onerous conditions. A number of alternative configurations are proposed which allow the management of transient recovery voltages within the breaker withstand level.**

***Index Terms*—Circuit breaker restrike and reignition, high-frequency transients, mechanically switched capacitor, transient recovery voltages (TRVs), wind turbine generator.**

I. Introduction

MECHANICALLY switched shunt capacitor banks are usually equipped with a series-connected inductor which limits the severity of the inrush current during capacitor energization and the outrush current during capacitor bus faults [1]. A common application of this configuration is where two capacitor banks are connected to the same bus bar or located in the vicinity of each other. This is generally termed as a back-to-back configuration, and associated switching studies are referred to as back-to-back switching studies. The use of a series-connected inductor and its inherent resistance allows a significant reduction in the inrush and outrush currents that would otherwise create excessive overvoltages potentially damaging the capacitor circuit breakers [2]. Note that, with capacitor banks, inrush and outrush currents generally have higher frequencies compared to those experienced with transformers.

When opening circuit breakers against a plain capacitor, the peak transient recovery voltage (TRV) is generally very low. This allows a successful interruption of current without any restrikes or reignitions. The use of a series inductor, however, gives rise to a very-high-frequency TRV for a fault in the capacitor bank(s) or between the inductor and the capacitor bank. This can create a very high rate of rise of recovery voltage (RRRV) which exceeds the withstand capability of the circuit breaker, ultimately causing a breaker failure [1], [3]–[8]. This phenomenon is primarily caused by the interaction of either the series inductor and stray capacitance of the vacuum circuit breaker [5], [6] or the series inductor and its stray capacitance [7], [8]. In both cases, a very-high-frequency TRV can be formed upon circuit breaker opening which can exceed the breaker ratings in terms of the TRV frequency and RRRV.

Surge arresters are usually connected at the load side of the capacitor bank as shown in Fig. 2. They are generally effective in limiting the magnitude of TRV but practically have no impact on limiting the RRRV. One of the most commonly used methods to mitigate the TRV problems is to use surge capacitors alone or together with a damping resistor (RC snubbers) which are connected between the line and ground. These methods reduce the overall frequency of the TRV and, hence, the RRRV. The disadvantages are that the peak value of the TRV can be increased (particularly with surge capacitors [4]) and the snubbers may be required at several locations. These locations can include the main buses and the secondary side of the transformers in addition to the series reactors themselves. Another option to mitigate fast TRVs is to apply the surge capacitors across the circuit breakers. This has the same advantages as the previous method. The disadvantages are that it would require a nonstandard design of the vacuum circuit breakers and, hence, the capacitor banks and a significantly large value of capacitance may be required to maintain an acceptable RRRV [4].

This paper investigates the most onerous TRVs that can be produced when using an inductor in series with the shunt capacitor banks. Practical mitigation techniques are investigated, and their effectiveness is demonstrated through PSCAD/EMTDC simulation case studies.

The simulation case studies discussed in this paper allow for the calculation of transient recovery voltages across the capacitor circuit breaker during opening and the investigation of circuit breaker restrikes and the possibility of a breaker failure. The optimal configuration of capacitor banks can be determined accordingly to limit the overvoltages within the dielectric withstand capability of the breaker.

II. Simulation Case Studies

A. System Under Consideration

The system used for simulation case studies consists of six 2-MW wind turbines connected to a relatively weak 20-kV grid

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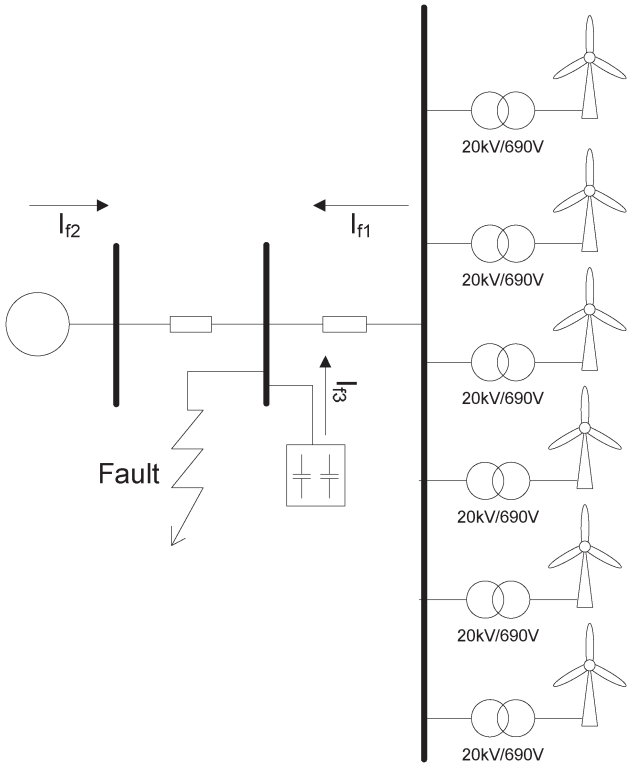

Fig. 1. Schematic diagram of the system under consideration.

with a short circuit ratio of 5 which is the ratio of the rms fault level at the point of interconnection, in megavoltamperes, to the nominal power of the wind farm in megawatts. The schematic diagram of the system under consideration is shown in Fig. 1. The detailed EMT model of the wind turbine generator representing the converter control and all other electrical protection and control systems is implemented in PSCAD/EMTDC. A discussion on modeling the detailed wind turbine generator used in this paper is given in [9]. The turbine model also includes a sufficiently accurate representation of the rotor-side and stator-side harmonic filters. At high frequency conditions caused by the operation of circuit breakers, other system impedances practically act as an open circuit, and filter impedances will be dominant. This methodology is further elaborated on in [10]. Note that this approximation is only valid for solidly grounded capacitor banks. Benchmarking studies carried out demonstrate that the TRVs investigated in this paper are sufficiently of high frequency such that the simplified representation will have a good correlation with the results obtained from the detailed EMT-type model. Space limitation does not allow reporting these benchmarking studies. For routine TRV studies, the simplified model can therefore be used, allowing a significant reduction in the overall simulation time. However, to ensure designing the most appropriate mitigation methods, all case studies discussed in this paper are conducted with the detailed EMT-type model of the WTG.

The models used for the vacuum circuit breaker, power cables, and surge arresters are described in [10]. The determination of the model parameters for the vacuum circuit breaker is elaborated in the Appendix. The validation of the integrated model of a wind power plant utilizing the models used in this paper is discussed in [11]. Various case studies indicate that the simulated responses generally have a good correlation with the actual field measurements, which gives confidence in the veracity of the individual models used.

B. Case Studies

1) Summary of the Results: Results obtained from reactive power compensation studies have indicated that two chunks of capacitor banks rated at 1.67 and 3.34 Mvar are required to maintain the statutory power factor range during conceivable operating conditions. The stray capacitances of the equipment generally have a significant impact on determining the RRRV. When conducting capacitor switching studies with solidly grounded capacitor banks, the picofarad-range stray capacitances are outweighed by the microfarad-range capacitance of the shunt capacitor bank and can be neglected without compromising the accuracy of the results.

Several case studies are conducted to identify the most onerous overvoltages that can be imposed on the capacitor bank circuit breakers. Simulation case studies presented in this paper are summarized in Table I where case 2 represents the original configuration of capacitor banks. In all figures except Fig. 14, the series-connected resistors represent the internal resistance of the inductor rather than an intentionally designed damping resistor. The scenarios that do not give rise to excessive overvoltages have been precluded. Numerous simulation runs have identified that a three-phase-to-ground fault at the source side of the two capacitor banks causes the highest TRV. This fault condition has therefore been applied for all case studies discussed in this paper as highlighted in Fig. 1. It is a normal practice to use surge arresters for capacitor bank protection, and therefore, case studies with surge arresters have only been included. A temporary self-extinguishing fault is applied such that the fault lasts for 60 ms from the inception. At this time, the circuit breaker poles are proceeding with the opening sequence. The following assumptions have been made with regard to the operation of the two circuit breakers.

1) The two vacuum circuit breakers for the capacitor banks will initiate the first opening attempt simultaneously.
2) The three circuit breaker poles operate simultaneously.
3) The first opening attempt for the three poles of the two circuit breakers is initiated 80 ms after the fault inception.

In summary, the sequence of events applied is as follows.

1) At $t = 2.596$ s, a three-phase-to-ground fault is applied at the point shown in Fig. 1.
2) The temporary fault is extinguished at $t = 2 = 6.656$ s.
3) The two vacuum circuit breakers initiate their first opening attempt at $t = 2.676$ s.

The point on the wave operation of circuit breakers has been adjusted such that very short arcing times are achieved, and therefore, the most onerous switching operations are investigated. Note that the use of different filter configurations causes a shift in the current zero crossing. For some of the cases considered, the timings specified earlier have therefore been shifted by a few microseconds such that identical arcing times are achieved in all cases. The conclusions made from various

TABLE I
SUMMARY OF SIMULATION CASE STUDIES

Case ID	Correspondig Figures	Capacitor bank configuration	Grading capacitor?	VCB dielectric withstand capability (kV)	Breaker operation successfull?
1	2,3	Plain capacitor with capacitor neutral grounded	×	37	✓
2	4,5	Single tuned with capacitor neutral grounded	×	37	×
3	6,7	Single tuned with capacitor neutral grounded	✓	37	×
4	8	Single tuned with capacitor neutral grounded	×	45	✓
5	9,10	Single tuned with inductor neutral grounded	×	37	×
6	11,12	Single tuned with inductor neutral grounded	✓	37	✓
7	13	Single tuned with inductor neutral grounded	×	45	✓
8	14,15	C-type filter with inductor neutral grounded	×	37	✓

case studies can therefore be compared directly. Different fault duration and breaker opening times can be considered without impacting the general conclusions made.

In all cases, the neutral point of the capacitor banks is connected to the ground as this configuration is commonly used in wind power plants. Additional case studies would be required for capacitor banks with ungrounded neutral to confirm whether or not the same conclusions are valid.

The TRV withstand capability of the 20.5-kV vacuum circuit breakers used for capacitor switching studies is assumed to be 37 kV which is marginally higher than that obtained from the IEC 60056-1 [12]. Note that this parameter is the peak TRV rating of the circuit breaker which is defined as E_2 in ANSI C37.06 [13] and u_c when using two parameter representations described in the IEC standards [12], [14]. The impact of increased TRV withstand capability is investigated in a couple of case studies.

2) Case 1—Plain Capacitor With Capacitor Neutral Grounded and Dielectric Withstand Capability Set to 37 kV: The first case study investigates the impact of a three-phase-to-ground fault with the use of two plain capacitor banks rated at 1.67 and 3.34 Mvar as shown in Fig. 2. Note that, for all configurations discussed in this paper, a per-phase schematic diagram of the three-phase capacitor banks is shown. With this configuration, the circuit breaker is successful in interrupting the fault current without any restrikes or reignitions as illustrated in Fig. 3. With the introduction of the fault at $t = 2.596$ s, the fault current flowing into the circuit breaker can last for a couple of milliseconds only due to the fast discharge of the plain capacitor banks (directly connected without an inductor). This momentary fault current contribution is not therefore shown in Fig. 3 which starts from 2.6 s.

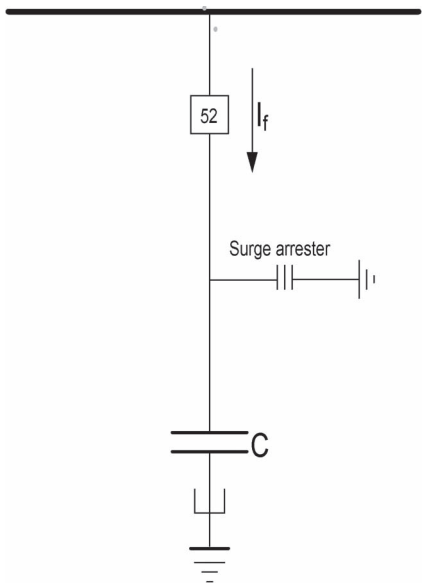

Fig. 2. Schematic diagram of the capacitor banks for case study 1.

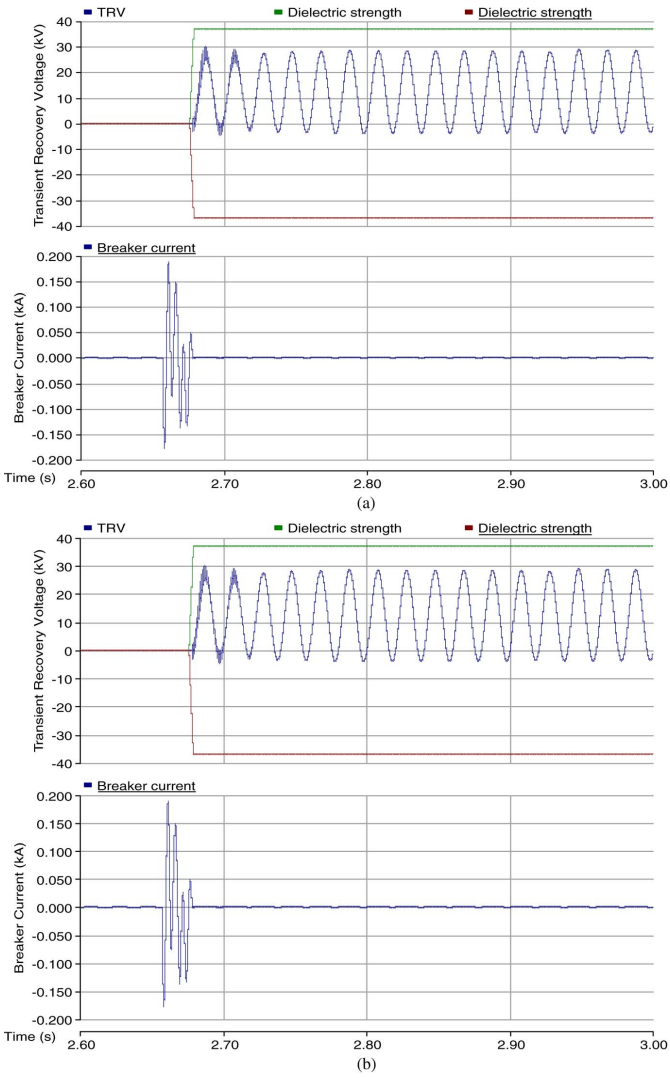

Fig. 3. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

3) Case 2—Capacitor Bank in Series With Inductor With Capacitor Neutral Grounded and the Dielectric Withstand Capability Set to 37 kV: In the original filter configuration, the current limiting inductors are connected to the source side of the capacitor as shown in Fig. 4. Fig. 5 shows the transient recovery voltage across pole A of each circuit breaker without the use of any overvoltage mitigation method. This figure indicates excessive overvoltages in terms of magnitude and RRRV. Once the breaker poles start to open, the initial TRV peak exceeds the dielectric withstand capability of the breaker which causes a number of restrikes as shown in the figure. These restrikes have extremely steep rise time and high dv/dt with a time to peak of approximately 2 μs. A voltage escalation occurs with the overvoltages reaching approximately 56 kV. The breaker keeps on restriking which results in a breaker failure. This behavior is due to the combination of the series inductor and stray capacitance of the circuit breaker which results in a high-frequency TRV exceeding the circuit breaker ratings in terms of the TRV frequency.

As shown in Fig. 5, the introduction of the fault at $t = 2.596$ s would result in some initial fault currents in the

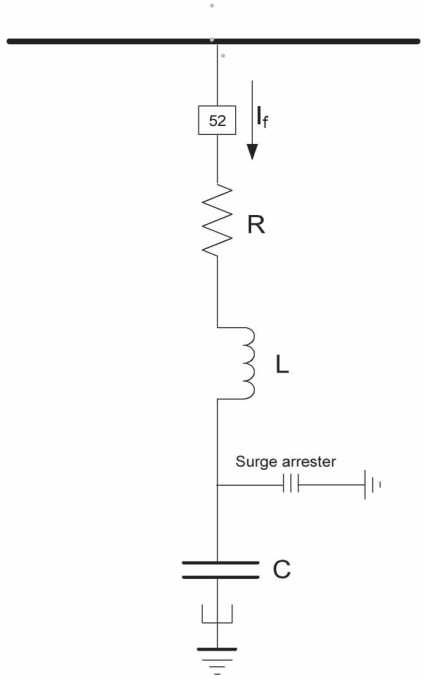

Fig. 4. Schematic diagram of the capacitor banks for case study 2.

circuit breakers until the fault is extinguished at $t = 2.656$ s. With this configuration, most fault current flows through the inductor due to its lower impedance compared to the capacitor.

4) Case 3—Capacitor Bank in Series With Inductor With Capacitor Neutral Grounded, With Grading Capacitor, and the Dielectric Withstand Capability Set to 37 kV: The use of a grading capacitor along with the surge arrester does not ensure a satisfactory operation of the vacuum circuit breaker during opening as shown in Fig. 6. Note that a grading capacitor is a small picofarad-range capacitor connected in parallel with the current limiting reactor which limits the RRRV. This configuration is illustrated in Fig. 7. The value of the grading capacitor is selected such that the resulting TRV is less than that specified in the IEC 60056 [6]. The grading capacitors used for this case study are accordingly rated at 20 pF. Further investigations revealed that increasing the size of the grading capacitors up to thrice the original value did not resolve the problem.

5) Case 4—Capacitor Bank in Series With Inductor With Capacitor Neutral Grounded and the Dielectric Withstand Capability Set to 45 kV: An additional case study was conducted using the configuration shown in Fig. 7 except that the dielectric strength was increased to 45 kV. This implies that the circuit breaker TRV rating has been increased to withstand higher peak TRV values. This will have the same net impact as using a circuit breaker with a higher voltage rating. Results shown in Fig. 8 demonstrate that, with this modification, the breaker restrikes are avoided. This solution, however, necessitates a significant modification in the breaker insulation, and purpose-built circuit breakers are therefore required.

6) Case 5—Capacitor Bank in Series With Inductor With Inductor Neutral Grounded and the Dielectric Withstand Capability Set to 37 kV: An alternative configuration to that

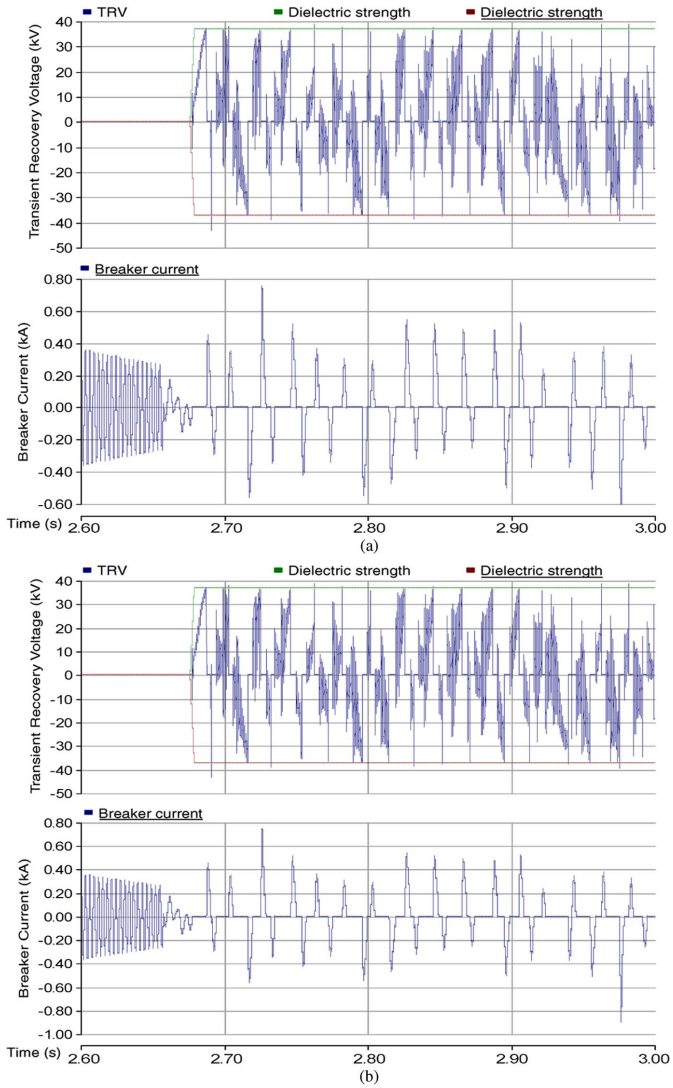

Fig. 5. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

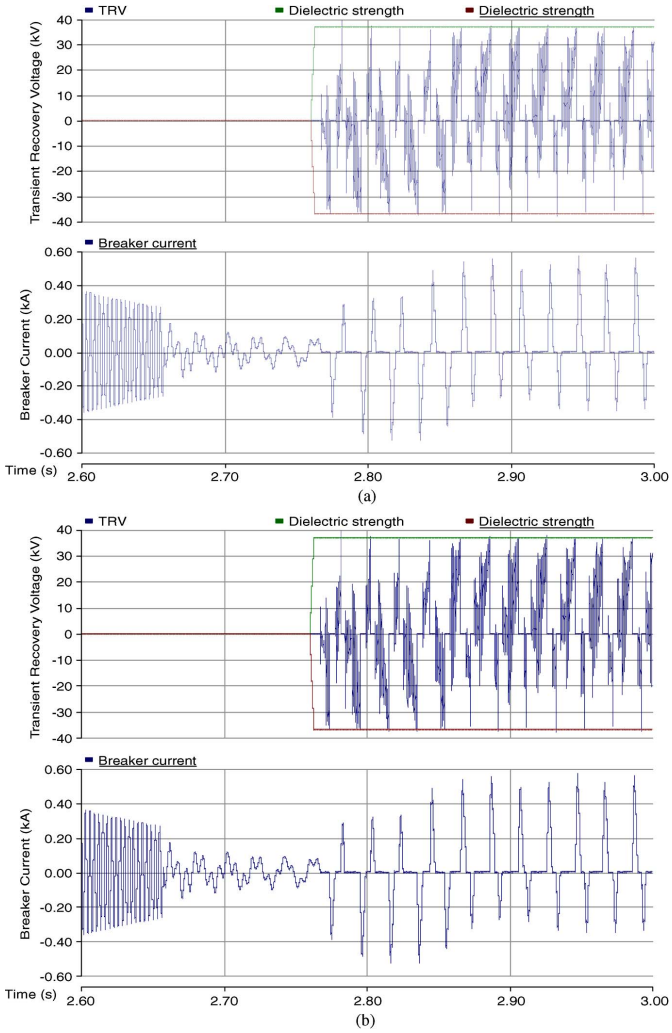

Fig. 6. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

discussed in cases 2–4 is to relocate the current limiting reactor to the neutral side of the capacitor bank. This configuration is shown in Fig. 9. Results obtained with this configuration are discussed in case studies 5–7. Fig. 10 indicates that, with the use of a surge arrester alone as a countermeasure, the resulting TRV exceeds the tolerable dielectric withstand capability of the breaker.

Note that the relocation of the capacitor would result in very little initial fault current in the circuit breaker compared to the original configuration. This is because the inductor is practically bypassed and the resulting fault current would be similar to the case with plain capacitor banks (which is not shown in Fig. 10 as the figure starts at $t = 2.6$ s).

7) Case 6—Capacitor Bank in Series With Inductor With Inductor Neutral Grounded, With Grading Capacitor, and the Dielectric Withstand Capability Set to 37 kV: The configuration shown in Fig. 11 includes a 20-pF grading capacitor in parallel with each phase of the inductors. With this configuration, the breaker will successfully open at the first current zero crossing without any restrikes as shown in Fig. 12.

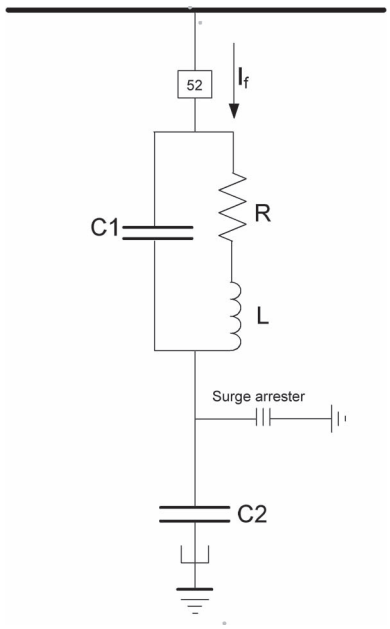

Fig. 7. Schematic diagram of the capacitor banks for case study 3.

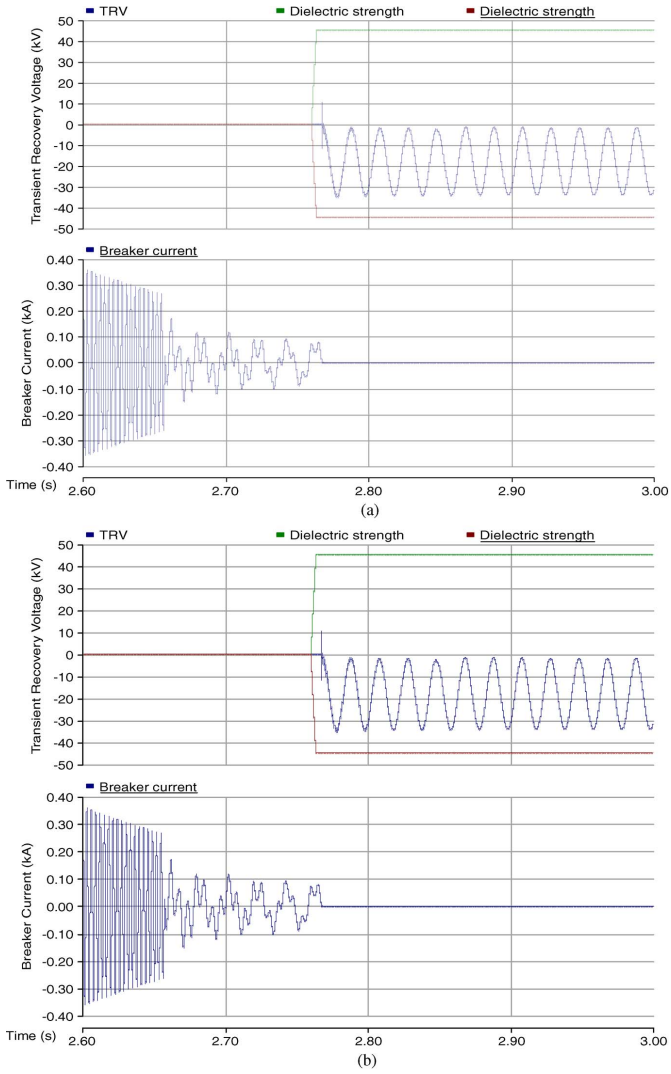

Fig. 8. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

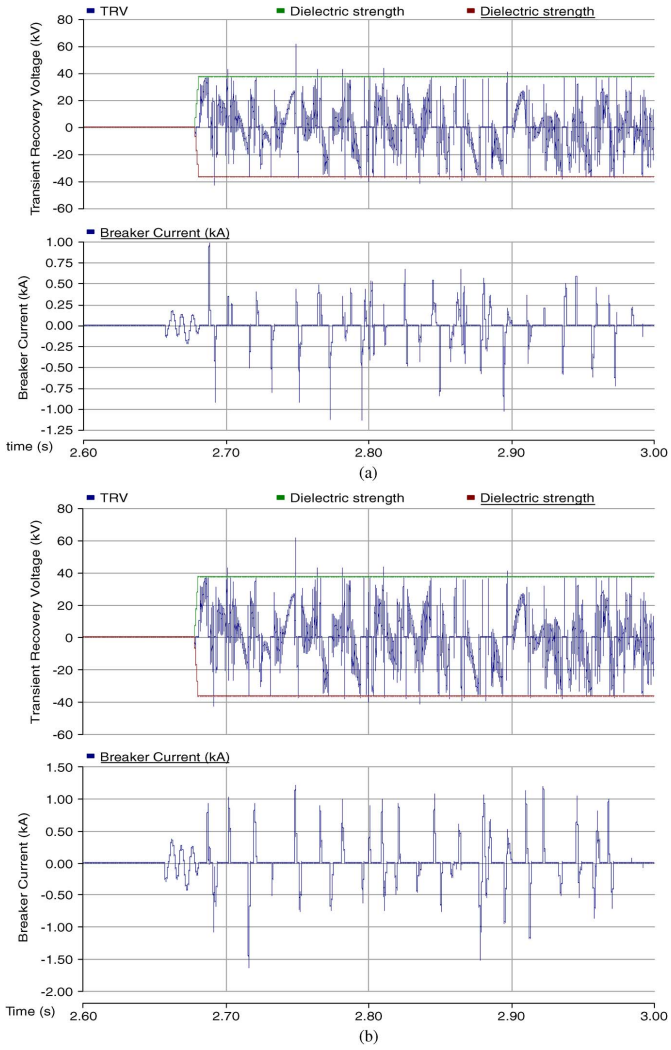

Fig. 10. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

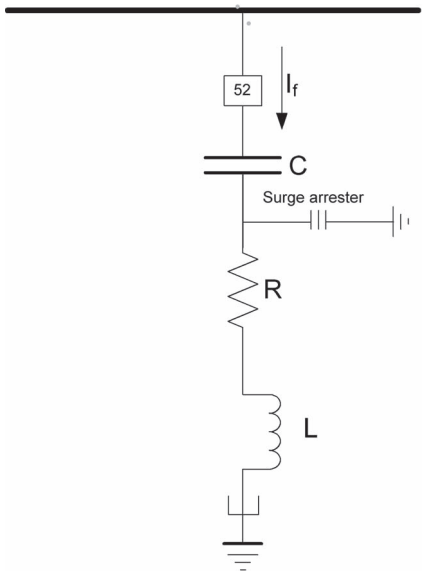

Fig. 9. Schematic diagram of the capacitor banks for case study 5.

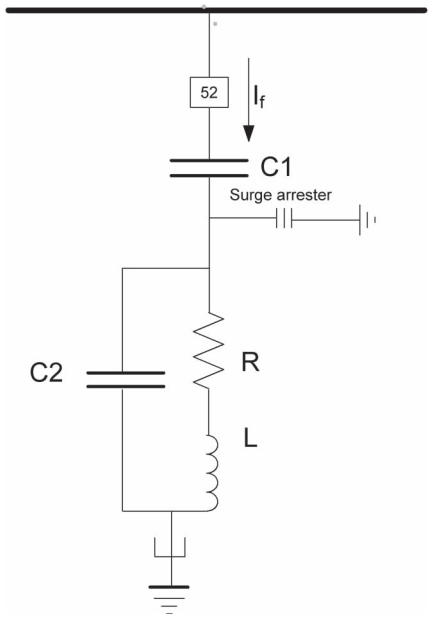

Fig. 11. Schematic diagram of the capacitor banks for case study 6.

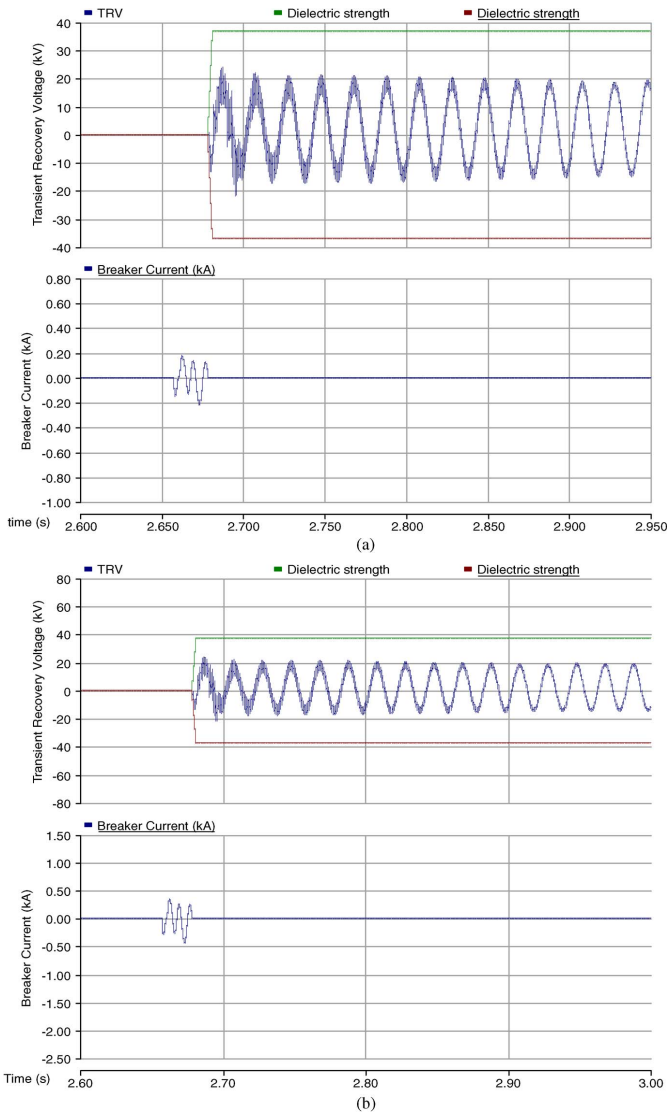

Fig. 12. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

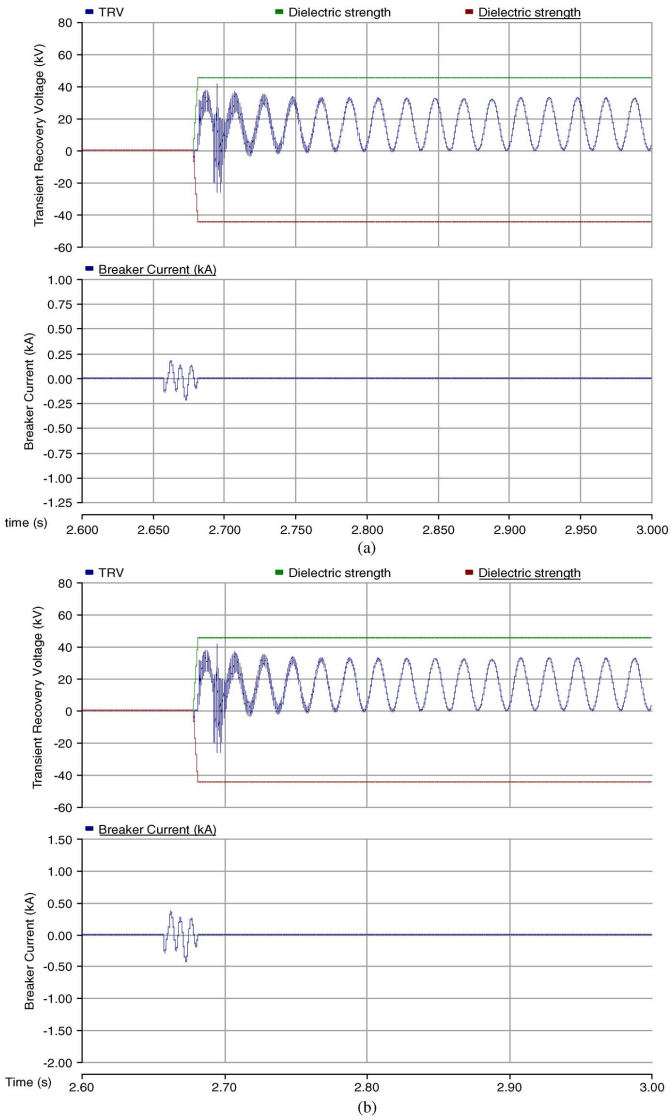

Fig. 13. TRV and breaker current for phase A of the capacitor bank breaker: (Left) 1.67-Mvar capacitor and (right) 3.34-Mvar capacitor.

8) Case 7—Capacitor Bank in Series With Inductor With the Inductor Neutral Grounded and the Dielectric Withstand Capability Set to 45 kV: Conclusions made in case study 6 remain valid when the dielectric strength of the breaker is increased to 45 kV as shown in Fig. 13. When relocating the current limiting reactor to the neutral side of the capacitor, the breaker failure can be avoided with the use of a grading capacitor which is generally a more practicable and economical solution compared to increasing the dielectric strength of the breaker.

9) Case 8—C-Type Filter [15] and the Dielectric Withstand Capability Set to 37 kV: Another alternative to avoid restrikes and subsequent breaker failure is to use a C-type filter instead of the capacitor bank in series with an inductor discussed earlier. In a C-type filter, an auxiliary capacitor is connected in series with the reactor as shown in Fig. 14 where the main and auxiliary capacitors are denoted as C1 and C2, respectively.

The reactor and auxiliary capacitor are chosen to form a series resonance at fundamental frequency. The impedance of the branch comprising the reactor and auxiliary capacitor is therefore zero at the fundamental frequency. The damping resistor is practically short-circuited at fundamental frequency, and a C-type filter produces negligible fundamental frequency losses. The reactive power rating of the filter is determined by the main capacitor only [15]. The two C-type filters have been designed to produce 1.67 and 3.34 Mvar with a Q factor of 300 [16] and a parallel resistance of 1000 Ω. Results shown in Fig. 15 indicate that, with a C-type configuration, the breaker failure is avoided without the need for a grading capacitor or increasing the dielectric withstand capability of the breakers.

Note that, with this configuration, the purpose-built series resistance R1 is two orders of magnitude larger than the inherent series resistance of all other configurations. This provides a high level of damping to the TRV. Additionally, the introduction of the capacitor C2 gives rise to a reduction in the TRV frequency and, hence, RRRV. This is because this capacitance will be dominant compared to the stray capacitance of the circuit breaker.

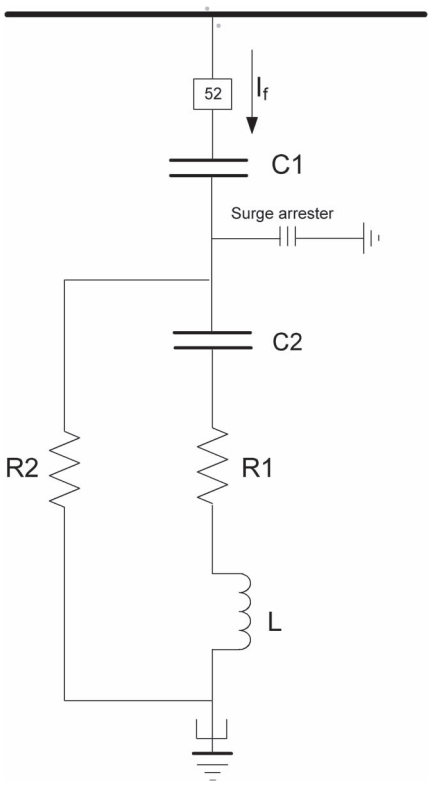

Fig. 14. Schematic diagram of the capacitor banks for case study 8.

III. Conclusion

This paper has presented a number of the most onerous switching studies for switching capacitor banks connected to the collector grid of a wind power plant. The simulation case studies have shown that the use of a current limiting reactor in series with each capacitor phase will create high-frequency overvoltages during current interruption. These overvoltages can exceed the dielectric withstand capability of the breaker in terms of the permissible magnitude and RRRV. Different capacitor bank configurations have been investigated. This includes single tuned banks with the series reactor connected to the source side or the neutral side of the capacitors and the use of C-type filter banks. It was shown that the use of C-type filters eliminates the need for any additional overvoltage mitigation measures. When connecting the current limiting reactor to the neutral side of the capacitor, the high-frequency overvoltages and consequent breaker failure can be prevented by the application of grading capacitors connected in parallel with the reactors. This measure has not been, however, proved to be effective when the reactor is connected to the source side of the capacitor. Another solution to mitigate the multiple breaker restrikes is to use a circuit breaker with a higher dielectric withstand capability, but this requires designing purpose-built breakers with accompanying higher costs.

Appendix

The vacuum circuit breaker model developed in PSCAD/EMTDC takes account of the dielectric strength, high-frequency current quenching capability, and current chopping capability of the breaker as discussed hereinafter.

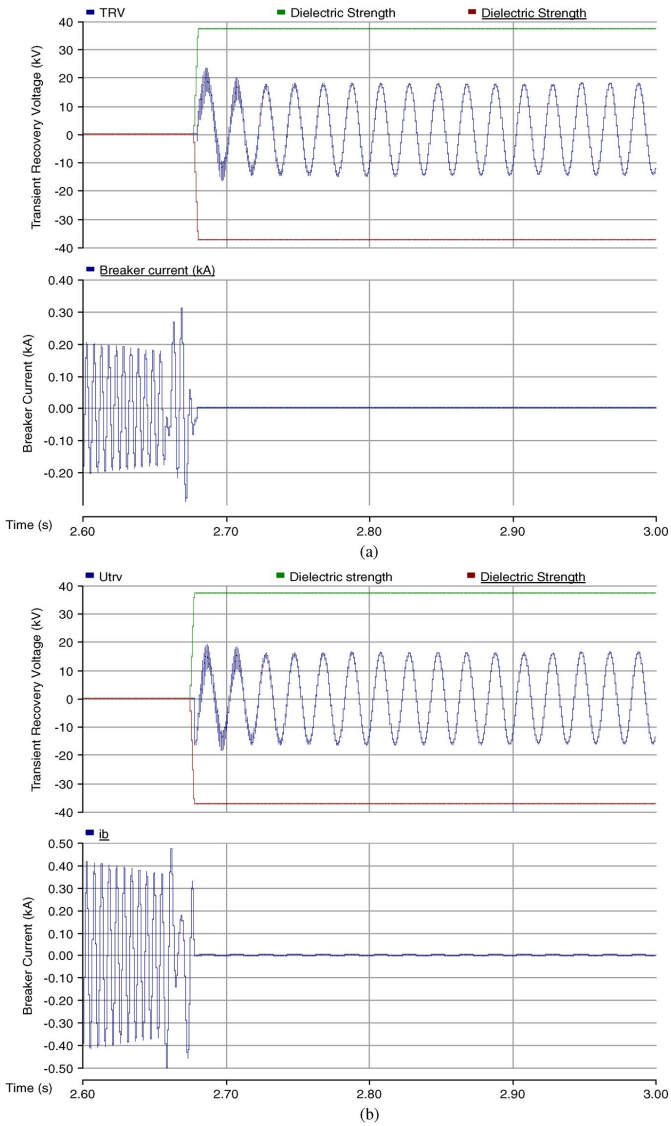

Fig. 15. TRV and breaker current for phase A of the capacitor bank breaker: (a) 1.67-Mvar capacitor and (b) 3.34-Mvar capacitor.

Dielectric Strength: Most relevant technical literatures assume a linear variation of the dielectric strength during opening and closing [17]. Measurements conducted on a similar vacuum circuit breaker (VCB) have indicated that a quadratic function provides a better match as represented by (A.1) [18]

$$V_{\mathrm{br,withstand}} = At^2 + Bt + V_0. \tag{A.1}$$

For closing operation, a linear function was used as indicated by

$$V_{\mathrm{Br,withstand}} = A_a(t - t_c) + B_b \tag{A.2}$$

where t_c indicates the moment of contact closing.

This equation has an initial value B_b that represents the dielectric strength just after the contacts have separated and a constant A_a that represents the closing speed.

TABLE II
VCB MODEL PARAMETERS FOR INVESTIGATION OF BREAKER OPENING AND CLOSING OPERATION

VCB model parameters	Aa	Bb	Cc	Dd	A	B	V_0
Closing (linear)	5×10^7	0	0	3.5×10^6	N/A	N/A	N/A
Opening (quadratic)	N/A	N/A	0	3.5×10^6	5.25×10^9	4.15×10^6	1200

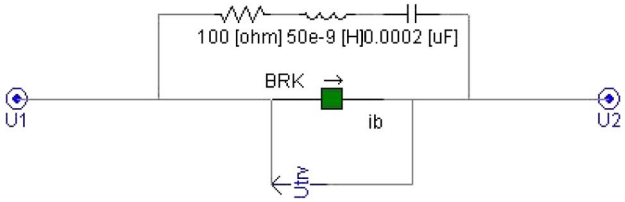

Fig. 16. Electrical circuit of the breaker.

High-Frequency Current Quenching Capability: The high frequency current quenching capability of the VCB can be generally represented as [17], [18]

$$\text{di/dt} = C_c(t - t_0) + D_d. \tag{A.3}$$

The term di/dt represents the highest current derivative that the breaker can break at a current zero crossing. For this study, the di/dt is set to 350 A/μs, consistent with the value obtained from the measurements reported in [18].

Current Chopping: The current chopping component of the VCB model represents the conventional low frequency current chopping. Phenomena such as virtual current chopping which can involve significantly higher frequencies are catered for in the model by the high-frequency current quenching capability component discussed earlier. The model developed in PSCAD/EMTDC includes an algorithm that ensures that only one chopping occurs after the breaker has received the signal to initiate the opening. This means that only the power frequency current is chopped. The value of current chopping provided by the VCB vendors is typically in the range of 3–9 A. The default value of current chopping is set to 5 A which is the maximum chopping current stated by a few vendors of the VCBs applied for capacitor banks in wind power plants. The default value can be readily changed in the model if VCBs with different levels of current chopping are used.

Parameter Settings: Using different values for coefficients A_a, B_b, C_c, and D_d as reported in [17] and [18], arcing times in the range of 2–18 ms can be obtained. The choice of parameters has a significant impact on the performance of the breaker. With the use of *medium*-range values indicated in [17] for the dielectric strength and a constant current quenching capability, an arcing time of 6 ms is obtained. This is considered as a sufficiently onerous condition to investigate the impact of transients on the circuit breaker and the impact of breaker restrikes and prestrikes on the power system. The corresponding coefficients for breaker opening and closing are shown in Table II.

The electrical circuit of the vacuum circuit breaker represented in PSCAD/EMTDC is shown in Fig. 16, indicating a value of 2 pF for the stray capacitance of the VCB.

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