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Transient Analysis and Mitigation of Capacitor Bank Switching on a Standalone Wind Farm

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Abstract**—**There exist significant losses on transmission lines due to distance, as power generating stations could be located far from some isolated settlements. Standalone wind farms could be a good choice of alternative power generation for such settlements that are far from the grid due to factors of long distance or socio-economic problems. However, uncompensated wind farms consume reactive power since wind turbines are induction generators. Therefore, capacitor banks are used to compensate reactive power, which in turn improves the voltage profile of the network. Although capacitor banks help improving voltage profile, they also undergo switching actions due to its compensating response to the variation of various types of load at the consumer's end. These switching activities could cause transient overvoltage on the network, jeopardizing the end-life of other equipment on the system. In this paper, the overvoltage caused by these switching activities is investigated using the IEEE bus 14-network to represent a standalone wind farm, and the simulation is done using ATP/EMTP software. Scenarios involving the use of pre-insertion resistor and pre-insertion inductor, as well as controlled switching was also carried out in order to decide the best mitigation option to reduce the overvoltage.

Keywords**—**Capacitor banks, IEEE bus 14-network, Pre-insertion resistor, Standalone wind farm.

I. Introduction

GLOBAL warming is currently a major cause of concern and the need for renewable energy which are clean and environmentally-friendly to relieve conventional sources of energy has been the priority of most countries of the world [1]. The issue of the daily increase in demand for power and the fear of depletion of conventional power in the future has also helped the development of renewable energy as an alternative source. Wind energy being a source of renewable energy stands out from other renewable energy sources as a technology which has significantly developed over the decades, thus gaining lots of attention. With 23% growth in the last decade and 369.6 GW installed wind power at the end of year 2014, wind energy can be said to be a leading renewable energy [2]. Renewable energy as regards power systems can be implemented either by standalone systems or grid-connected systems. Standalone renewable energy was proffered by the World Bank as a potential solution to the energy-poverty issues, which is seen as a major set-back in developing countries with 77% of Sub-Saharan Africa not having access to energy services [3]. Judging from cost of transmission and the fact that the reduced usage of conventional energy would help lessen the effect of global warming, the standalone wind farm is a good suggestion for settlements far from the grid. Viability of a standalone wind farm is not power generation alone, but could be used for other applications such as pumping of water, and also serves as a flexible electricity source for charging the standalone battery needed in the evolution of the electric vehicle. Standalone wind farms can either be small or large depending on the installed wind turbine to meet the required power demand.

The main problem concerning wind energy is voltage variation which is caused by fluctuation of wind speed ranging from minutes to months [4]. Another cause of voltage variation is as a result of different types of load, especially loads with low power factor at the consumer's end. Most of the loads are induction motor including the wind turbine itself. Hence, the stator winding consumes the excitation current causing the current to lag the voltage, this could cause poor voltage regulation, among other effects, reducing the efficiency of power transmission. In solving this problem, the use of a capacitor bank is employed to compensate the reactive power absorption by inductive elements on the wind farm. It achieves this task by storing reactive power and supplying it when inductive elements rave for it. However, switching of capacitor banks can cause stress on the wind farm that could greatly shorten the life expectancy of the other equipment on the wind farm [5], [6]. During the energization, transient inrush current can be observed, while during de-energization, huge overvoltage could be experienced. Factors such as size of the capacitor bank that is being switched, the type of load at the consumer's end and short circuit characteristics of the system affect the amplification of the transient voltage during the switching activities [7]. In this paper, switching actions of capacitors are investigated considering the transmission system of a standalone wind farm and the use of various methods of mitigating the transients are evaluated.

II. Model

In modelling the switching activities of capacitor banks on the transmission system of a standalone wind farm, IEEE bus 14-network is used. A typical IEEE bus 14-network is shown in Fig. 1 consisting 5 generators, 11 loads and 14 buses.

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A. Generator

The five generators on buses 1, 2, 3, 6 and 8 were modelled each on ATP/EMTP as a group consisting wind turbine, wind turbine transformer, and cables as shown in Fig. 2.

The wind turbine was modelled as a voltage source of 690 V with a fault level of 1 MVA and source impedance of 0.48 Ω. Small length cable of 20 m cable connecting the wind turbine to the transformer and the main cable 400 m are modelled by RLC PI equivalent. The wind turbine transformer rated 25 MVA, 0.69/66 KV is modelled with BCTRAN model. The overhead transmission lines 25 km are modelled using PI model.

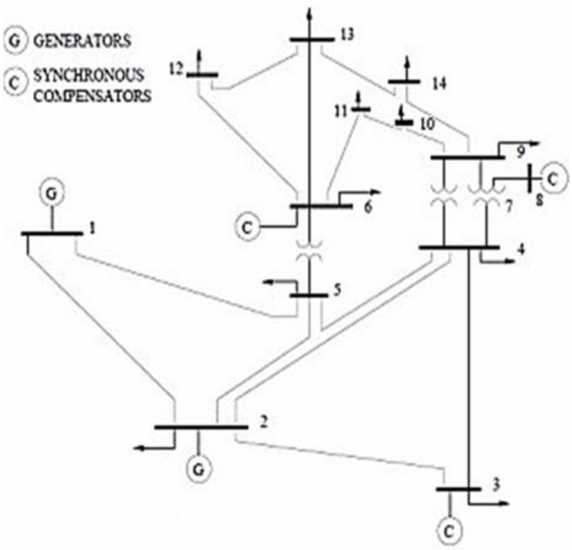

Fig. 1 Typical IEEE bus 14-network [8]

B. Connected Load

Different Loads are connected on buses 2, 3, 4, 5, 6, 9, 10, 11, 12, 13 and 14, modelling them as RL lump parameter with power factor ranging from 0.81 to 0.86. The values for lump parameter are calculated using (1) and (2):

$$R = \frac{U_p^2}{P} \tag{1}$$

$$L = \frac{U_p^2}{2\pi f Q} \tag{2}$$

where U_p is the system voltage, P is the rated power of the system, L is the load inductance, R is the resistance of the load, Q is the reactive power of the system and f is the natural frequency of the system.

A. Capacitor Banks

Capacitor banks 900 KVAr, 1,200 KVAr and 1,800 KVAr are placed on buses 3, 6 and 8, respectively. The value of the capacitor placed in the model is obtained by (3):

$$C = \frac{Q}{2\pi f U^2} \tag{3}$$

Fig. 3 shows the model of the IEEE bus on ATP/EMTP consisting all the components discussed in this section.

III. Capacitor Bank Energization

By energizing, the capacitor bank is closed to the bus, this could cause a phenomenon called inrush current. Large inrush current could cause breakdown to protection system, therefore posing a major threat to devices on the system. During energization, the worst case that could be experienced is for the capacitor bank to close on the bus at the peak voltage (90^o). The probability of this occurring on any of the three phases is high since typical breakers close all three phases at the same time. Two cases of energization were simulated.

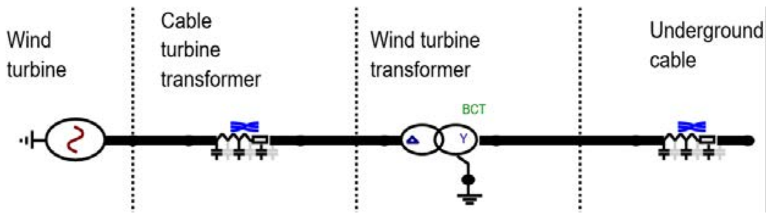

Fig. 2 Components grouped in the modeled generator

A. Case 1: Single Capacitor Bank Energization

In this case, energizing of the uncharged capacitor bank at voltage peak is considered. Fig. 4 shows a single-phase illustration of single capacitor energization; the inductance of the source is significantly larger than the inductance of the cable connecting the capacitor to the system ($L_s \gg L_c$).

Inrush current caused by energization of a single capacitor bank is about 5 P. U. and accompanied by frequencies of 200 to 600 Hz [9] depending on factors mentioned earlier that amplifies the transient. Theoretically, the inrush current can be obtained by (4), the surge impedance of the system is obtain by (5) and the natural oscillation frequency is given by (6) [10]:

$$I_t = \frac{U_p}{Z_o}\sqrt{\frac{2}{3}} \tag{4}$$

$$Z_o = \sqrt{\frac{L_s + L_c}{C}} \tag{5}$$

$$\omega = \frac{1}{\sqrt{(L_s + L_c)C}} \tag{6}$$

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In simulating single capacitor bank energization in this paper, 900 KVAr only is connected at bus 3. The capacitor bank was closed at 40.1 ms, the maximum inrush current observed is 1038 A as shown in Fig. 5.

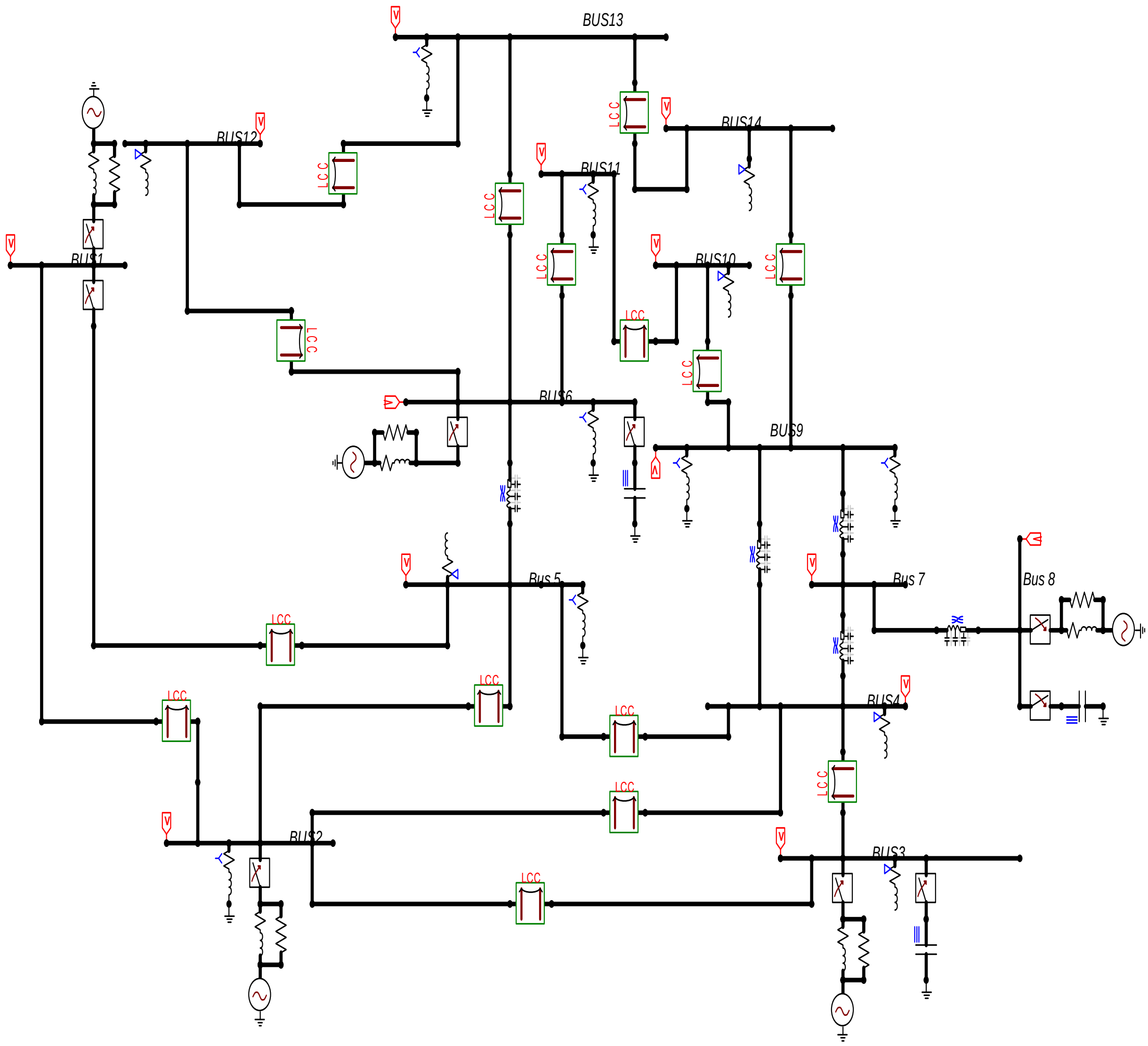

Fig. 3 Modelled IEEE bus 14-network representing standalone wind farm

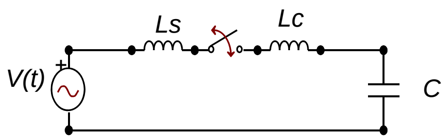

Fig. 4 Line representation of single capacitor bank energization

An overvoltage of 1.78 P.U as shown in Fig. 6 was observed for the energization scenario.

B. Case 2: Back-to-Back Capacitor Bank Energization

It is a common practice to install equivalent numbers of smaller capacitor banks instead of a large capacitor bank in order to make the compensating system more reliable and flexible. However, this configuration causes back-to-back switching, where one capacitor bank is already energized and other capacitor bank is energized after it when the voltage is at the peak. Inrush current accompanying back-to-back switching can be up to 100 P.U. with frequencies between 2,000 to 20,000 KHz [9] depending on the number of capacitor banks in the system. Fig. 7 shows a circuit with back-to-back configuration of two capacitor banks.

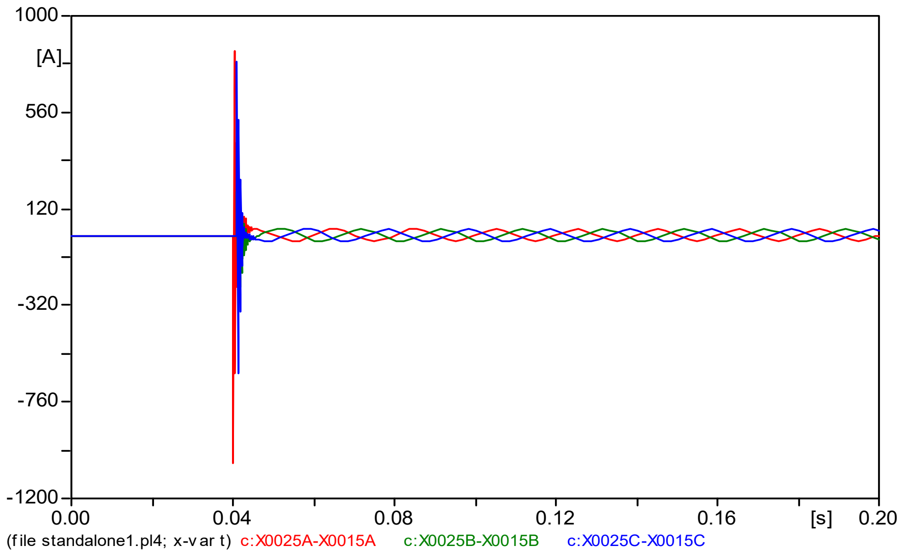

Fig. 5 Inrush current during single capacitor bank energization

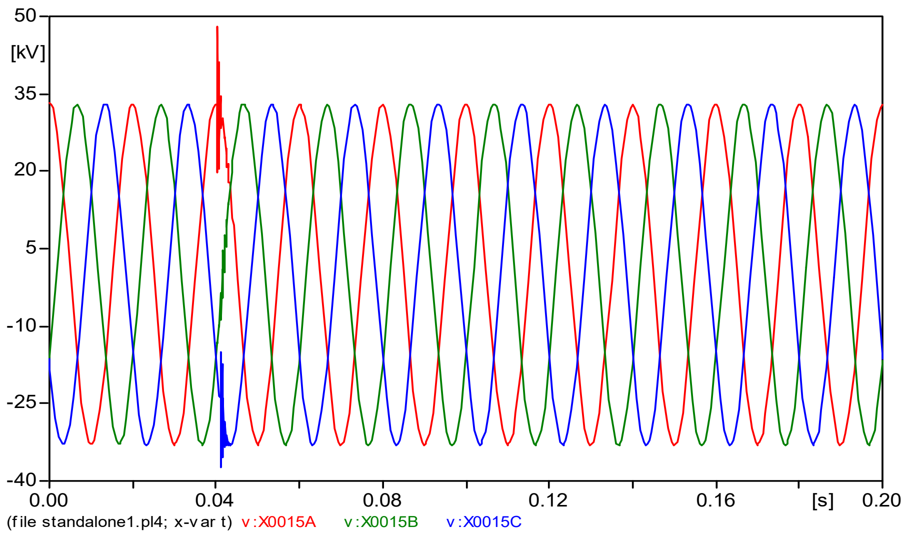

Fig. 6 Overvoltage caused by single capacitor bank energization

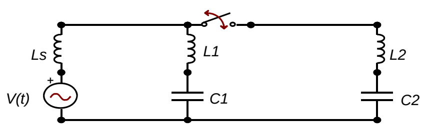

Fig. 7 Line representation of back-to-back capacitor energization

Inrush current can be obtained as (4), however, calculation for surge impedance of the circuit and natural oscillation changes can be obtained by (7) and (8):

$$Z_o = \sqrt{\frac{L_T}{C_T}} \quad (7)$$

$$\omega = \frac{1}{\sqrt{(L_T + C_T)}} \quad (8)$$

where,

$$C_T = \frac{C_1 C_2}{C_1 + C_2} \quad (9)$$

$$L_T = L_1 + L_2 \quad (10)$$

Simulating back-to-back energization in this study, two scenarios were considered. First scenario, the 900 KVAr bank on bus 3 has already been energized and operating in a steady state, while the 1,200 KVAr bank is energized at bus 6 when the voltage is at the peak. The 1,200 KVAr bank was closed at 40.1 ms, Figs. 8 and 9 show the observed maximum inrush current of 1,921.7 A and overvoltage of 1.43 P.U. respectively:

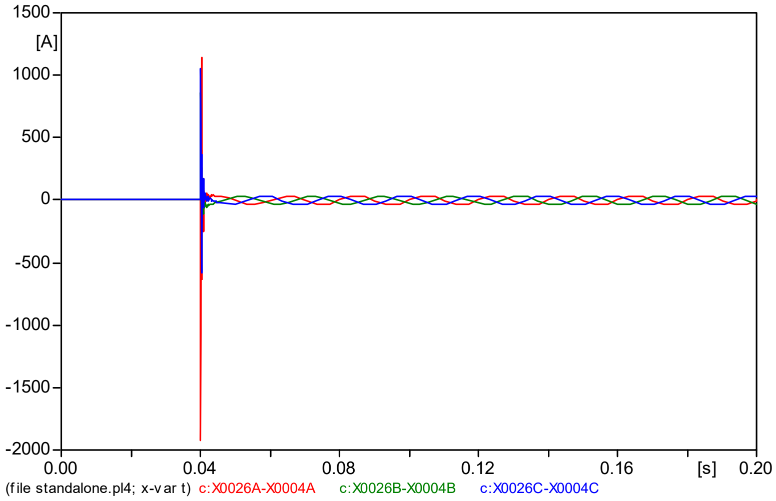

Fig. 8 Inrush current during back-to-back capacitor bank energization of 900 KVAr and 1200 KVAr

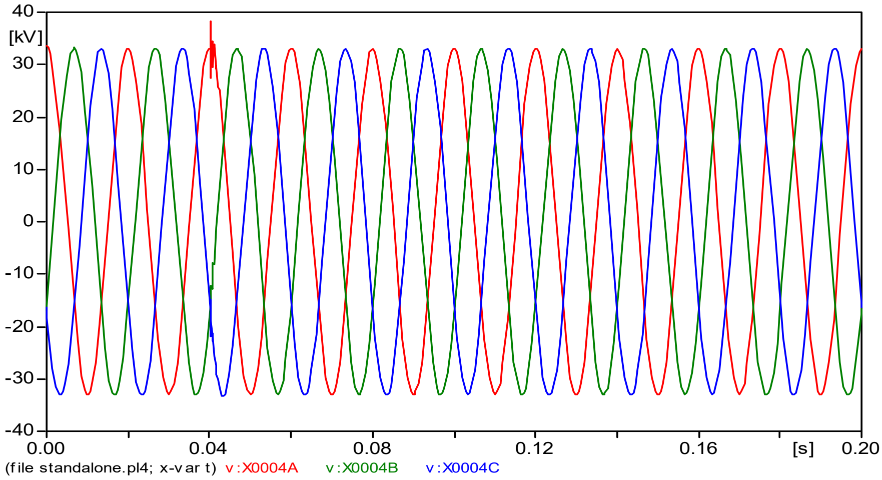

Fig. 9 Overvoltage caused by back-to-back capacitor bank energization of 900 KVAr and 1,200 KVAr

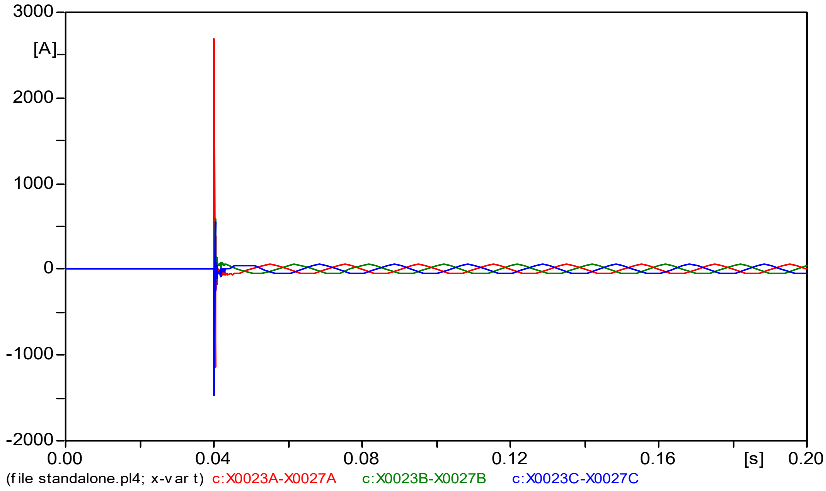

Fig. 10 Inrush current during back-to-back capacitor bank energization of 900 KVAr, 1,200 KVAr and 1,800 KVAr

The second scenario is such that 900 KVAr bank and 1200 KVAr bank on bus 3 and bus 6 respectively, has already been energized and operating in a steady state, while 1800 KVAr bank is energized at bus 8. A resultant maximum inrush current of 2681.5 A and overvoltage of 1.49 P.U. were experienced as shown in Figs. 10 and 11.

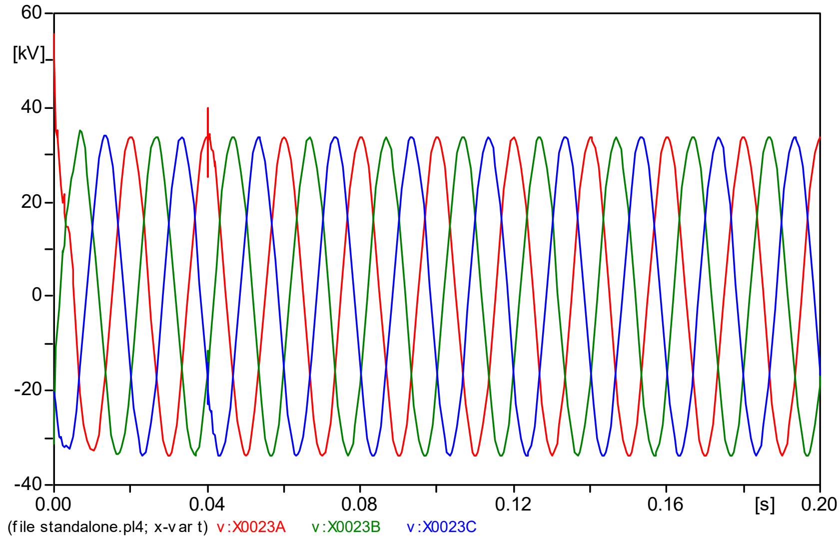

Fig. 11 Overvoltage caused by back-to-back capacitor bank energization of 900 KVAr , 1,200 KVAr and 1,800 KVAr

IV. Outrush Transient

Considering a scenario where the capacitor bank is already energized and operating in steady state and a fault occurs on the bus, the capacitor bank would discharge into the fault. This discharge is called outrush current, whose magnitude and frequency depend on inductance between the capacitor bank and the fault location. Outrush transient can be very severe if the inductance is in the order of tens of micro-Henries [7] causing huge stress for the circuit breaker and other equipment on the bus. Fig. 12 shows the circuitry representation of outrush current. Outrush current in the system can be determined by (4) while surge impedance of the system and natural oscillation and can be obtained by (11) and (12):

$$Z_o = \sqrt{\frac{L_c}{C}} \tag{11}$$

$$\omega = \frac{1}{\sqrt{L_C C}} \tag{12}$$

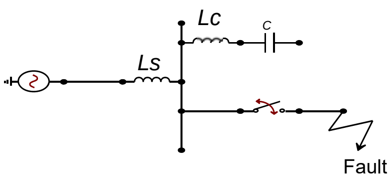

Fig. 12 Simple illustration of outrush transient

Outrush transient is simulated by connecting only 1200 KVAr bank on bus 6 while single phase-to-earth fault modelled on the bus is closed at 50.44 ms. Fig. 11 shows the observed outrush transient of 2117 A. The probability occurrence of outrush transient maybe twice in a year but the effect could be very severe.

V. Capacitor Bank De-Energization

De-energization of the capacitor bank can cause high overvoltage stress on the circuit breaker. During de-energization, the capacitor retains a DC trapped charge which is equal to the voltage at the time of interruption. If the interruption occurs just after current zero crossing, the voltage would happen to be at the peak since the phase difference between voltage and current is 90º. Sometimes, this may lead to restrike of the circuit breaker resulting in a high steep overvoltage of 4 P.U. According to the simulation done, Fig. 14 shows overvoltage as high as 2.46 P.U., with the voltage rising to 66.2 KV when the circuit breaker opened at 56.7 ms. This can be analytically calculated with (13), giving 2 P.U.

$$U_t = \frac{2\,U_p}{\sqrt{3}} \tag{13}$$

VI. Mitigation of Transient Using Pre-Insertion Resistor, Pre- Insertion Inductor and Pre-Impedance

A. Pre-Insertion Resistor

Pre-insertion resistor has been used for years in power systems in mitigating transient caused by energization of capacitor bank. A shunt resistor is provided across the circuit breaker as a bypass, which is closed before the capacitor bank is energized. It is arranged such that the movable part of the circuit breaker makes contact with the shunt resistor first before contacting the fixed contact energizing the capacitor bank. The resistor provides damping and reduces the transient energy. The pre-insertion resistor needed for this purpose is 40

Ω as it is commonly used. The overvoltage when pre-insertion is connected across 900KVAr during energization is reduced to 1.27 P.U with inrush current of 60.4 A as shown in Fig. 15.

B. Pre-Insertion Inductor

Pre-insertion inductor is set-up bypassed with its circuit switcher having a high-speed disconnecting blade, which switches in during the capacitor closing for 7-12 cycles depending on the system voltage [11]. Pre-insertion is frequency dependent; thus the value of the transient is large at the time of energization of the capacitor but it is reduced shortly after. During energization of the capacitor bank, the current leads the voltage by 90°, the pre-insertion inductor reduces the phase angle difference, thus reducing the oscillatory frequency of the transient. It is a common practice to use 40 mH, it is connected across 900 KVAr during energization. The overvoltage is reduced to 1.27 P.U. and 605.8 A inrush current experienced as shown Fig. 16.

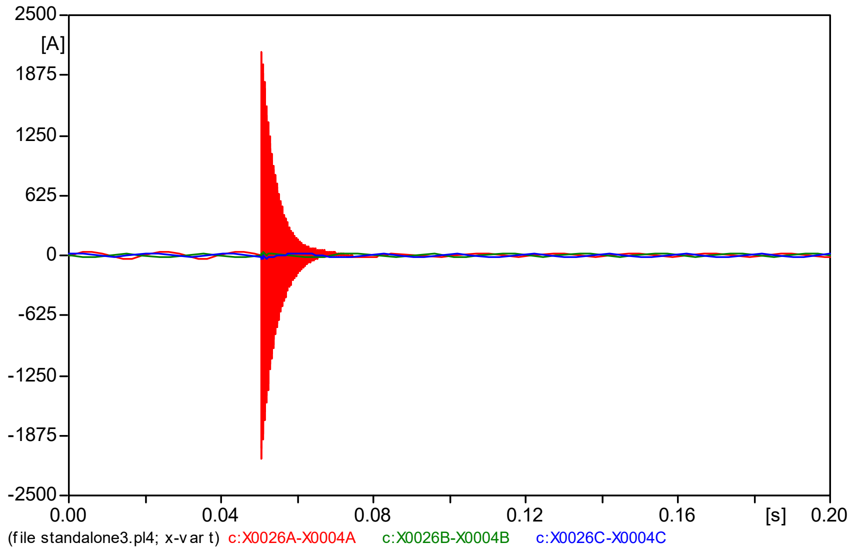

Fig. 13 Outrush transient observed on phase A

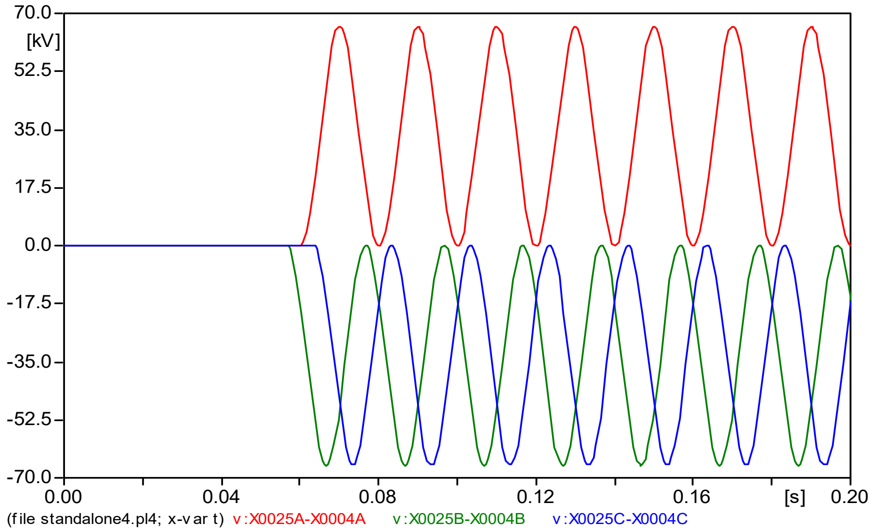

Fig. 14 Overvoltage across the circuit breaker during capacitor bank de-energization

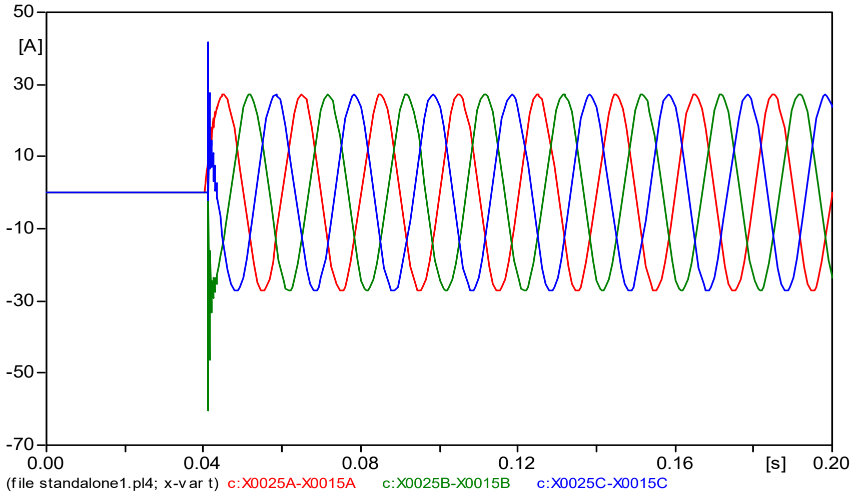

Fig. 15 Using pre-insertion resistor to migitgate the transient

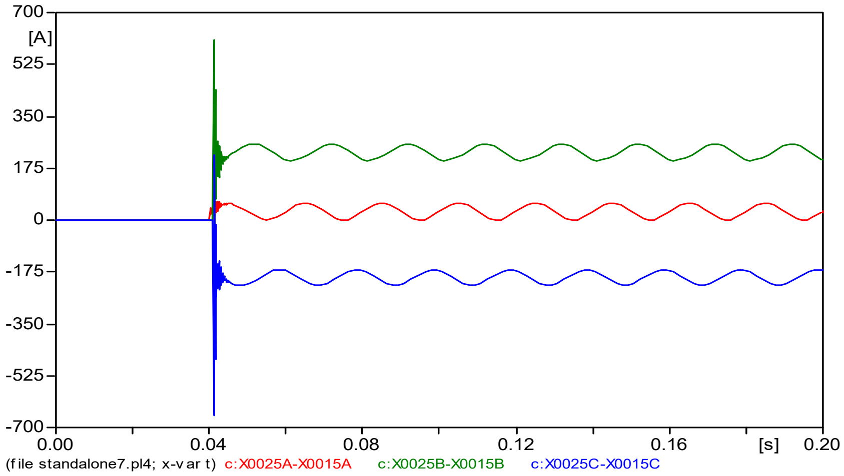

Fig. 16 Using pre-insertion inductor to migitgate the transient

C. Pre-Insertion Impedance

The use of pre-insertion impedance involves the use of resistor and inductor in series connected as a bypass across the capacitor. Pre-insertion impedance reduces the initial inrush current, as well as the voltage transient during the energization of capacitor bank. It also reduces the chance of the switching transient from having resonance with other LC circuits [11]. The pre-insertion impedance is switched out a few cycles after the transient is damped. Fig. 17 shows the resultant inrush current of 29.4 A and the overvoltage is reduced to 1.24 P.U. when pre-insertion impedance of 40 Ω resistor and 40 mH inductor is used.

VII. Use of Controlled Switching Device

Controlled switching has proven to be an effective means of mitigating switching transient. This solution allows the poles of the circuit breaker to operate individually. The switching actions of the relay is delayed to the time that least stress is experienced on the power system using the phase angle of either the voltage or the current. In the case of capacitor energization, the best time to close the breaker is when the system voltage is at zero. The zero-crossing time of one of the phases is needed while others can be calculated from the reference phase. In this model, using phase A as reference, the random closing signal issued at 40.1ms is delayed and phase A is closed at 55 ms. Controlled closing time of Phase B is 66.6 ms and phase C is 58.34ms. Resultant waveform of the controlled switching of the circuit breaker is in Fig. 18, the overvoltage is reduced to 1.23 P.U and the inrush current observed is 50.3 A.

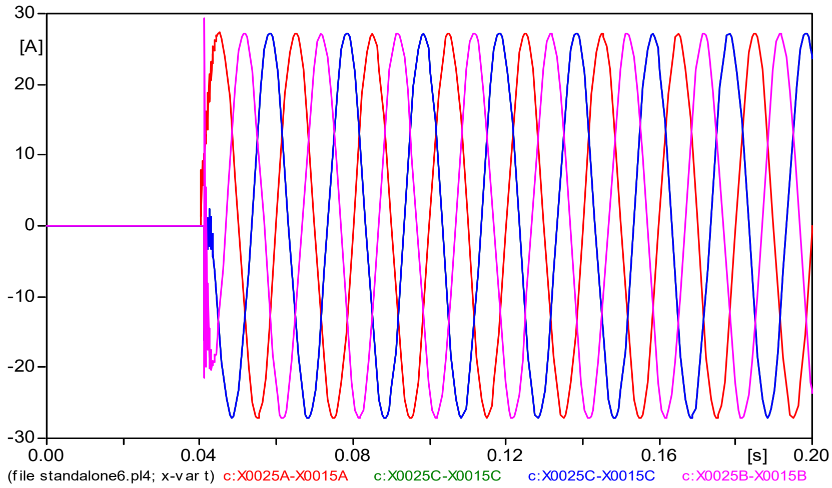

Fig. 17 Using pre-insertion impedance to migitgate the transient

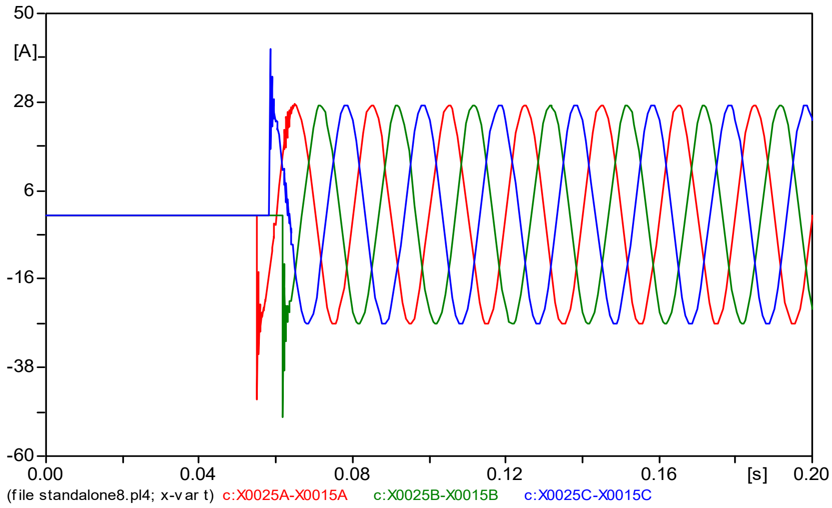

Fig. 18 Mitigation using controlled switching

VIII. Conclusion

Modelling and simulation done shows that energization of a capacitor bank can cause transient on a standalone wind farm. The case is worse when energizing a capacitor when one is already in operation. This raises the need for good mitigating technology. The mitigating method simulated shows that the use of pre-impedance is the best to mitigate the transient. The cost implication of choosing this method should be considered as synchronous switching also showed good potential of mitigation.

References

[1] I. M. Dudurych, M. Holly, and M. Power, "Wind farms in the Irish Grid: Experience and analysis," in *Power Tech, 2005 IEEE Russia*, 2005, pp. 1-7.

[2] G. w. energy. (2013, December, 2015). *2014 marked a record year for global wind power*. Available: http://www.gwec.net/global-figures/wind-energy-global-status/

[3] T. Van de Graaf and K. Westphal, "The G8 and G20 as global steering committees for energy: Opportunities and constraints," *Global Policy*, vol. 2, pp. 19-30, 2011.

[4] Z. Chen, "Issues of Connecting Wind Farms into Power Systems," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1-6.

[5] M. Iizarry-Silvestrini and T. Vélez-Sepúlveda, "Mitigation of Back-to-Back Capacitor Switching Transients on Distribution Circuits," *IEEE Transactions on Transmission Line*, 2008.

[6] M. McGranaghan, R. Zavadil, G. Hensley, T. Singh, and M. Samotyj, "Impact of utility switched capacitors on customer systems-magnification at low voltage capacitors," in *Transmission and Distribution Conference, 1991., Proceedings of the 1991 IEEE Power Engineering Society*, 1991, pp. 908-914.

[7] G. Gopakumar, H. Yan, B. A. Mork, and K. K. Mustaphi, "Shunt capacitor bank switching transients: A tutorial and case study," in *Minnesota Power Systems Conference*, 1999.

[8] M. Kezunovic and J. Ren, "New test methodology for evaluating protective relay security and dependability," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-6.

[9] A. T. D. s. Expertise, "Introduction to Switching of Shunt Capacitor Banks," 2007.

[10] A. Greenwood, "Electrical transients in power systems," 1991.

[11] E. Camm, "Shunt Capacitor Overvoltages and a Reduction Technique," in *IEEE/PES Transmission and Distribution Conference and Exposition New Orleans, LA*, 1999, pp. 180-T72.