Investigation and Analysis of Temporary Overvoltages Caused by Filter Banks at Onshore Wind Farm Substation

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Abstract— Parallel resonance generated by capacitive elements on the wind farm amplifies the current distortion caused by harmonic emission from the wind turbines and results in high voltage and current distortion through the transmission equipment connected to the grid. Similarly, series resonance amplifies the harmonic voltage distortion from the HV bus to MV bus, causing the same effect. Harmonic filters are used to screen out the unwanted harmonic effects on the wind farm. The switching activities of the harmonic filter bank may cause overvoltages on the onshore wind farm substation, thus, they are investigated in this paper with the aid of ATP/EMTP software. Temporary overvoltages caused by energising and de-energising of the filter were investigated to understand whether they exceed the withstand limits of the system. It was found that the overvoltages for both energization and denergization were beyond the power frequency withstand level. By then using statistical studies on the mitigation methods, it was found that the use of pre-insertion resistors and surge arresters greatly mitigated the overvoltage caused by energization.
Keywords— Harmonic Filters, Temporary Overvoltage; Pre-Insertion Resistors; Wind Farm.

1. Introduction

Of the several power quality issues affecting wind power, harmonic resonance has been of major concern and this has prompted research from various authors [1-4]. The wind farm contains capacitive and inductive elements such as wind turbine generators, compensation devices, transformers and underground cables. These devices are located at various voltage levels and the interactions of these elements raise the harmonic effect on the wind farm. The harmonic resonance effect is highly observable at the source (wind turbine generator), at the point of common coupling (PCC) and on the transmission system (onshore substation). The harmonic current source is from the wind turbine generator which injects harmonic currents causing parallel resonance when the harmonic currents are excited by the reactive components resonant points. Moreso, power electronic devices such as STATCOMs, other FACTS devices and converters also contribute to the harmonic emission which could increase the level of distortion in the system. Due to the inductance and capacitance in series, harmonic voltage reflects from the grid which causes a series resonance effect when excited by small impedance resonant point [1]. There is a need to install wind turbine harmonic filters close to the wind turbine to filter out these harmonics. Despite this, the harmonic resonance is still observed at the PCC and on the both the offshore and onshore substation since the wind farm network has a number of inductive-capacitive elements. The need for the main wind farm filter on the onshore substation cannot be overemphasized due to the effects of harmonic current from the wind turbine and the ambient grid distortion at the PCC. The switching in and out of the harmonic filters necessary for mitigating the harmonics could pose an overvoltage problem on the onshore station.

According to[5], overvoltage can be classified based on their shape and duration in which they exist, hence they can be majorly divided into two: temporary overvoltage and transient overvoltage. Transient overvoltages are highly damped overvoltage with short duration of few milliseconds or lessand they include; slow-front, fast-front overvoltage and very fast-front overvoltage. Temporary overvoltages occur at a frequency close to the power frequency and can last for a long period, up to few seconds, which can be weakly damped or undamped. Cases leading to temporary overvoltage are load rejection, line energization,, fault clearing, reclosing transformer energization, resonance and ferroresonance. Papers such as but not limited to the following [6-9] have done research on the temporary overvoltage as regards to wind farm but the effect of switching activities of harmonic filters on the onshore substation have not been considered by these literatures. This paper studied the temporary overvoltage that could occur during switching activities of the harmonic filters on the onshore substation of a wind farm. Firstly, the level of harmonic distortion on the onshore substation was determined and appropriate harmonic filters were determined for mitigation purpose. Even though the overvoltage experienced is for a period lasting more than two cycles, it causes heating effect and majorly mechanical stress on the power equipment on the system. This could gradually lead to increasing voltage stress levels depending on the frequency of switching occurrence of the filters. Furthermore, the increasing voltage stress levels could be degrading the insulation of the power device to a point of flashover, reducing the age of the device. This could eventually cause the total dielectric breakdown of the insulation and the device could fail. Overvoltages during energization and denergization were investigated and possible methods of mitigation were also examined.

2. Harmonic Resonance in Transmission System

The effect of harmonics on a transmission system depends on the harmonic current amplitude and the transmission impedance characteristic. If a transmission system has large impedance at a particular harmonic frequency, a significant voltage distortion may be experienced at that frequency. The transmission system of a wind farm has high X/R ratio, such that the harmonics can propagate for longer distance due to lengths of overhead and submarine cables. The submarine cable contributes capacitance 20 times larger than overhead cable of the same distance to the transmission systems[10]. Also it is expected that capacitive characteristic of the overhead and submarine cable would increase as their length increases, hence impacting on the harmonics. A wind farm layout is shown in Fig. 1, with the main harmonic filter located at onshore wind farm substation.

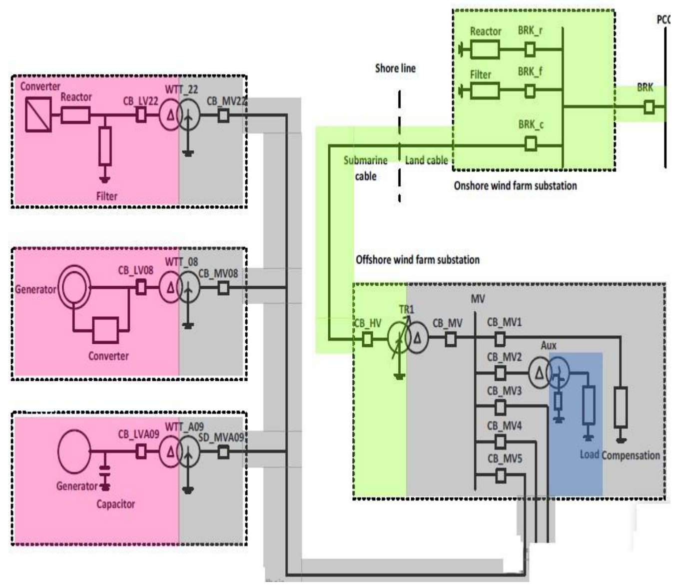

Figure 1. Layout of a wind farm[11]

A wind farm transmission system consists of the offshore substation as well as the onshore substation as shown in Fig. 1. Harmonics on the onshore substation should be mitigated because it could be a major source of harmonics for the rest of the transmission network after it. To determine the harmonic level present on the onshore substation, a frequency scan of the whole wind farm was conducted and harmonic orders with high level of harmonic distortion were observed on the onshore station. Assuming that the system is symmetrical, the wind farm is represented as a single phase, with the wind turbine modelled as a current harmonic source with the values obtained [12], while other components of the wind farm are modelled using their equivalent circuit as shown in Fig. 2.

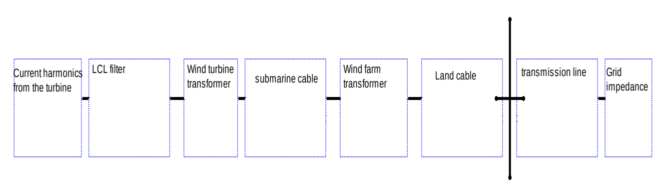

Figure 2. Single phase equivalent circuit of the wind farm

The observed harmonic impedance on the onshore substation is shown in Fig. 3, it is noticed that high level of harmonics occur at 5^{th}, 7^{th} and 11^{th} order. The lower order of harmonics up to 3^{rd} order from the wind turbine has been suppressed by the LCL filter located close to the turbine. Hence, single tuned filters are used to countermeasure the effects of these harmonic orders. The filters are connected via circuit breakers which switch the filters in and out as the need may be. Although harmonic filters are used in mitigating the harmonic problem on the wind farm, it could cause issues of overvoltage due to its switching activities. The onshore wind farm substation was modelled to investigate the switching activities of filters with appropriate countermeasures.

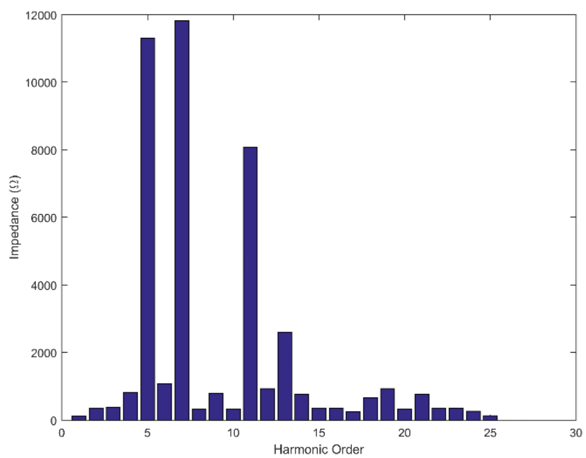

Figure 3. Harmonic impedance observed at onshore substation

3. Model

In modelling the switching activities of high harmonic filters on the onshore of wind farm, the use of ATP/EMTP software was employed. The generated voltage from the wind turbines is 690 V and it is stepped up by the wind turbine transformer to 33 kV. The voltage is further stepped up to 132 kV by the main wind farm transformer on the offshore wind farm. To investigate the switching of the harmonic filters, the layout of a wind farm as shown in Fig. 1 was represented on ATP/EMTP from the offshore substation to the onshore substation. So, the system voltage of the model is at 132 kV, and the permissible rated short duration power frequency withstand voltage is 150 kV. Fig. 4 shows the diagram of the components modelled between the offshore substation to the onshore substation.

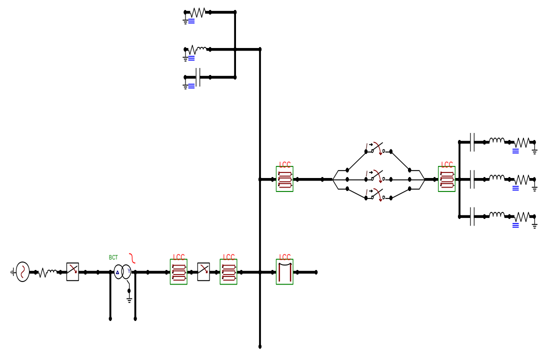

Figure 4. Simplified model of offshore substation connected to onshore substation on a wind farm

3.1. Source and Transformer

The offshore substation is represented by voltage source of 33 kV and the main wind farm transformer. The 33 kV voltage source was modelled with a fault level of 1000 MVA and source impedance 1.089 **Ω**. Table I, shows the data of the main wind farm transformer 132/33 kV as it is represented by using BCTRAN model on the ATP; since the accuracy of the simulation is frequency dependent, the nonlinearity of the transformer is considered.

Table 1. Details of the transformer

Parameter	Value
Vector group	Dyn11
Rated power	200 MVA
Open-circuit voltage (%)	100
Open-circuit current (%)	0.3
Open-circuit losses (kW)	90
Short-circuit impedance HV-LV (%)	10
Short-circuit impedance losses (kW)	500

3.2. Cables and Transmission Line

The onshore substation is connected by a 50 km three 630 mm^2 submarine cable from the offshore substation and it is terminated at the shore by land cable of 10 km three core 600 mm^2. Harmonic filters were connected on the onshore wind farm substation through a 200 m long single core cable. The feeder cables connected to the filter were modelled using the PI model. Submarine cable and the land cable were modelled using the JMarti model considering the length of the cables. The onshore network was modelled with overhead line of 160 km using the JMarti model considering frequency dependency of the model. All cables are modelled based on [13] with information obtained from manufacturer's data sheet[14].

3.3. Filters

Single tuned filters (5th, 7th and 11th) are modelled using lumped parameters (Fig. 5). The values for R_f, L_f and C_f are determined by (1), (2) and (3). Lump parameters of the single tuned filters used are in Table II.

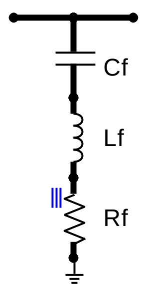

Figure 5. The single tuned filter configuration

$$C_f = \frac{n^2\text{-}1}{n^2} \cdot \frac{Q_f}{\omega U^2} \quad (1)$$

$$L_f = \frac{1}{n^2\omega^2 C_f} \quad (2)$$

$$R_f = \frac{2\pi f L_f}{Q} \quad (3)$$

Where n is the harmonic order, Q_f is reactive power of the filter, U is the operating voltage, ω is the natural frequency, Q is the quality factor, C_f is the capacitance of the filter, L_f is the inductance of the filter and R_f is the resistance of the filter.

Table II. Lump parameter of the single tuned filter

Parameter	Q_f(MVAr)	R_f(Ω)	C_f(µf)	L_f(mH)
5th	20	4.3561	3.507	115.6
7th	20	2.9254	3.5786	49
11th	20	1.9962	3.623	23.1

A compensating shunt reactor (80 MVAr) is also connected on the busbar to neutralize the effect of the capacitive elements. This was modelled according to [15].

4. Energization

By energizing, the harmonic filter was closed to the power systems, 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 substation. The overvoltage caused by the energizing is characterized by two phenomena: the energization of the feeder cable connecting the filter to the substation contributes to the inrush current due to the capacitive nature of the cable and the closing action of the circuit breaker energizing the harmonic filters. Characteristic impedance of a cable is about ten times smaller to that of transmission line[16]. This resultantly allows cables to exhibit ten times higher derivative of the transient as compare to transmission line. Hence, effects of travelling and reflection wave phenomena can even be observed in very short cable. The surge impedance of the cable is approximately 40 **Ω**. Inrush current that can be experience as a result of energizing the cable is given by (4):

$$I_t = \frac{U_p}{Z_c}\sqrt{\frac{2}{3}} \quad (4)$$

Where, U_p is the instantaneous voltage of the source at the closing time and Z_c is the surge impedance of the cable.

The second phenomenon is the overvoltage caused by the energizing action of the filter itself as the capacitors of the filter are charging. The resultant voltage across the filter at energization can be calculated to be the sum of the steady state voltage component and the voltage surge component at the point of closing as shown in (5):

$$V_f(t) = \frac{I_p.\sqrt{2}}{\omega.C_f}\left(\cos(\psi+\varphi).e^{-\frac{t}{\tau}} - \cos(\omega t+\psi+\varphi)\right) \quad (5)$$

The accompanying maximum inrush current can also be calculated by the sum of the steady state current component and the current surge component (6):

$$I_f(t) = I_p.\sqrt{2}\left(-\frac{1}{\omega.C_f}\cos(\psi+\varphi).e^{-\frac{t}{\tau}} + \sin(\omega t+\psi+\varphi)\right) \quad (6)$$

Where I_p is the instantaneous current, φ is the angular displacement between voltage and current, ψ is the angle at which the filter is energized while, τ is the time constant of the system and it is obtained as (7):

$$\tau = \frac{L_T}{R_T} \quad (7)$$

Where R_T is the total resistance, ω is the natural frequency of the undamped oscillation, given by (5):

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

$$L_T = L_f + L_s + L_{Tr} \quad (9)$$

Where L_f and C_f are components of the filter as shown in Fig. 5, L_S is the source inductance and L_{Tr} is the inductance of the transformer which can be calculated from the parameters of the transformer in Table I.

During energization, the worst scenario that could be experienced is for the breaker to be closed at the peak voltage (90°), there is a probability of this happening on any of the three phases in an attempt to close all the phases at the same time. The filter was energized at 40.1 ms which falls on the peak voltage of phase A. The maximum inrush current observed is shown in Fig. 6.

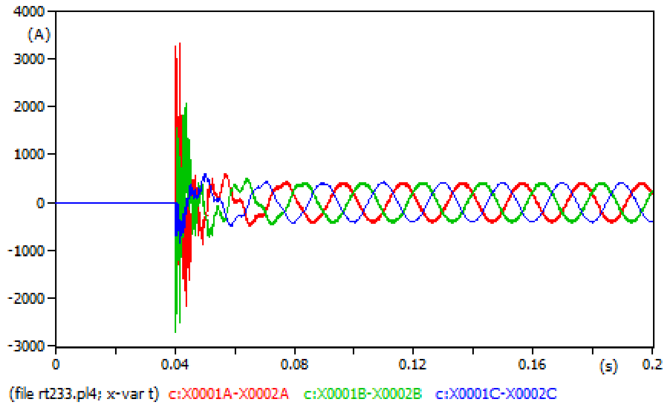

Figure 6. Inrush current during energization

An overvoltage of 1.53 P.U as shown in Fig. 7 was observed for energization scenario. The resistance of the system especially the damping nature of the shunt reactor caused the reduction of the 2 P.U overvoltage which is supposed to be observed according to theoretical analysis. This is above the permissible limit of the rated power frequency voltage level.

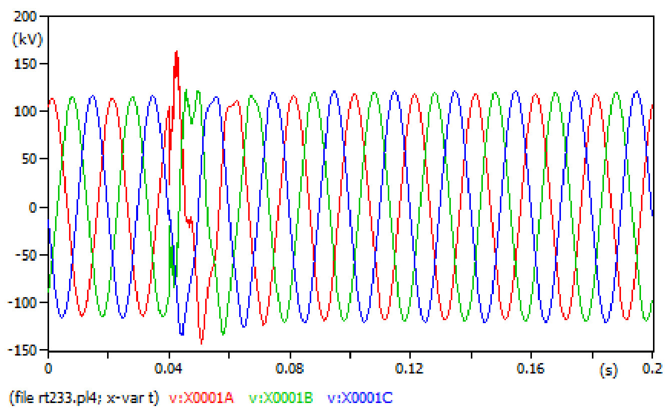

Figure 7. Overvoltage caused by energization

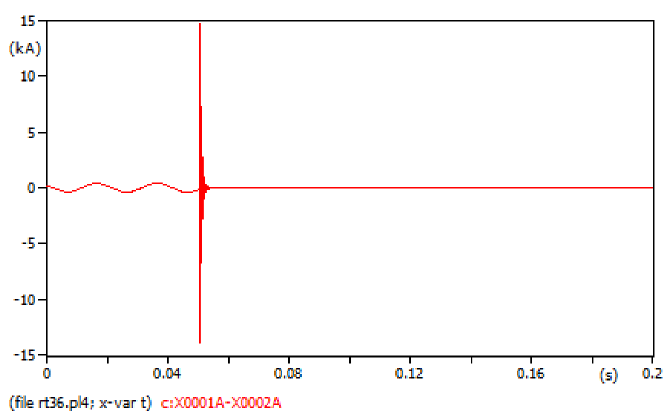

Figure 8. Overcurrent caused by reclosing to a fault

Another case of energization is reclosing. In this case, the filter is already energized and operating in a steady state, while a feeder on the busbar is closed to a fault. The capacitor C_f of the filter is already charged and any event of reclosing on the substation could cause a huge stress on the filter. In modelling the reclosing scenario, it was assumed that a phase to earth fault occurs on the busbar at 50.44 ms after the filters were energized. An overcurrent experienced at phase A is shown in Fig. 8.

5. De-energization

Opening of the filter can cause high overvoltage stress on the substation. During de-energization, the filter retains a DC trapped charge which is equal to the voltage at the time of interruption[17]. 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. According to the simulation done, Fig. 9 shows overvoltage as high as 2.67 P.U., with the voltage rising to 288.5 kV when the circuit breaker opened at 56.7 ms. This is way higher the rated short duration power frequency level. It can be analytically calculated with (10), giving 2 P.U.

$$V_F = \sqrt{2}\, V U_p e^{\frac{-t}{\tau}} \tag{10}$$

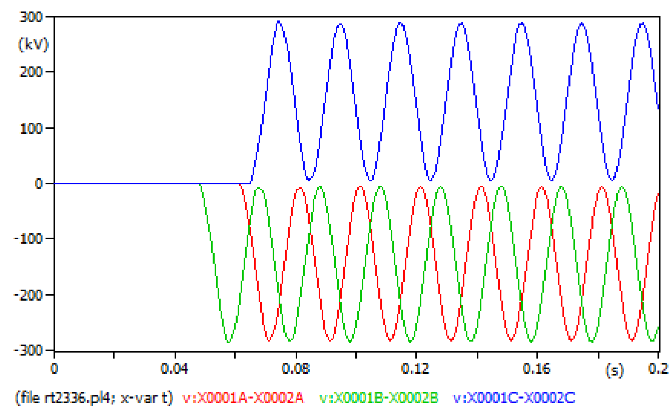

Figure 9. Overvoltage across the circuit breaker during de-energization

6. Mitigation Of Overvoltage Using Pre-insertion Resistor And Surge Arrester

Mitigation measures would be needed if the observed overvoltage is greater than the withstand level of the harmonic filter, this could cause total damage of the filter. For this reason, the mitigating effect of pre-insertion and surge arrester are used.

6.1. Pre-insertion resistor

A shunt resistor is provided across the circuit breaker as a bypass, which is closed before the filter is energized. The resistor provides damping and reduces the surge energy. The pre-insertion resistor needed for this purpose was calculated to be approximately 100 Ω by the use of (11):

$$R_{pr} = \frac{1}{2}\sqrt{\frac{L_T}{C_T}} \tag{11}$$

The resultant waveform of the simulation in Fig. 10 shows that 1.20 P.U overvoltage is experienced on the substation.

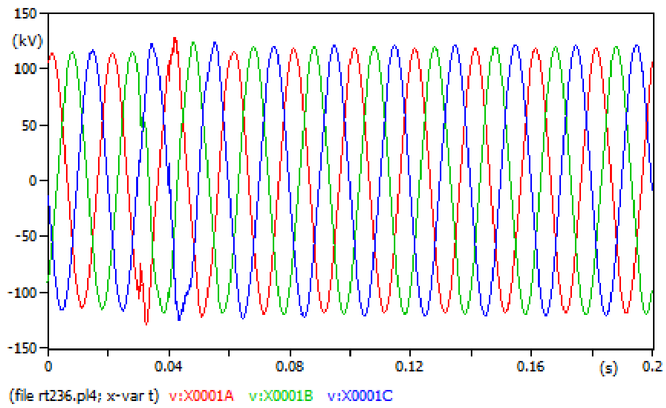

Figure 10. Using pre-insertion resistor to migitgate the overvoltage

6.2. Surge arrester

Surge arresters can limit surge to the arrester's protective level typically between 1.8-2.5 P.U. at the point of application [18]. However, the location of the surge arresters in the circuit could determine its ability to limit the surge. There are existing models of surge arrester, Metal-oxide surge arrester used in this study was modeled after IEEE model[19]. The V-I characteristics of the two nonlinear resistors were obtained according to IEEEANSI C62.11-1993 standard, for switching studies, the value of the residual voltage was estimated for current impulse of 10KA and 30/60µs as compared with the data presented by the manufacturer in [20]. The surge arrester was placed between the feeder cable and the circuit breaker, which is the best position that could limit the overvoltage [21]. It reduced the overvoltage produced during energization to 1.12 P.U as shown in Fig. 11.

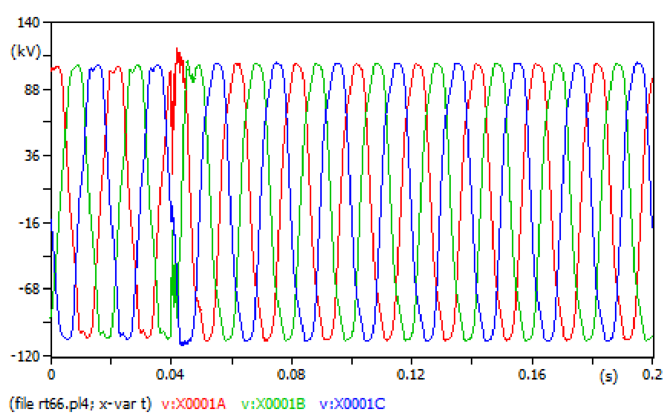

Figure 11. Using surge arrester to mitigate the overvoltage

6.3. Combination of pre-insertion resistor and surge arrester

The combination of pre-insertion resistor and surge arrester provided a better option of mitigation by damping and reducing the energy accompanying with the overvolatge. Effective reduction of the overvoltage to 1.04 P.U as shown in Fig. 12

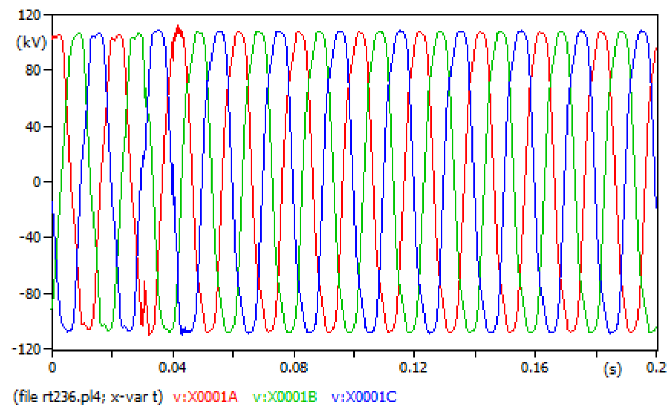

Figure 12. Using the combination of pre-insertion resistor and surge arrester to mitigate the overvoltage

6.4 Controlled Switching Device

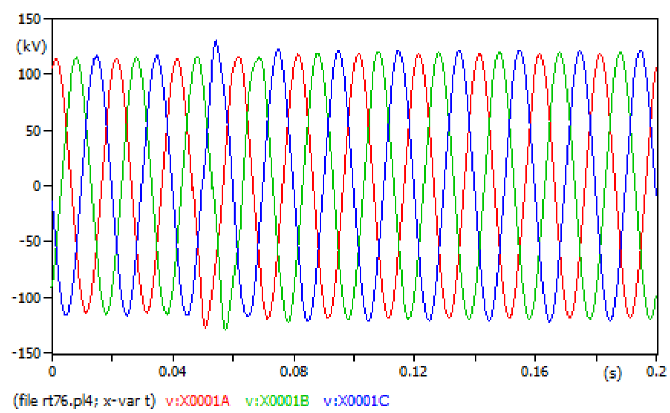

Figure 13. Mitigation by controlled switching

Controlled switching otherwise known as synchronous switching has proven to be an effective means of mitigating switching overvoltage. 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 applying controlled switching to mitigate the overvolatge observed in this study, each pole of the circuit breaker is expected to closed at voltage zero-crossing in order to minimize the overvoltage. Zero-crossing time of one of the phases is needed while others can be calculated from the reference phase. For instance, if the phase A closes, phase B and C are expected to close at 120 and 60 degrees respectively after phase A. In the present model, using phase A as reference, the random closing signal issued at 40.1ms is delayed 5ms to give a controlled closing time of 45.1ms. Controlled closing time of Phase B is 51.68ms and phase C is 48.34ms. Voltage waveform of the controlled switching of the circuit breaker is shown in Fig. 13, resulting to 1.22 P.U.

7. Statistical Analysis Of Mitigation Methods For Energization Scenario

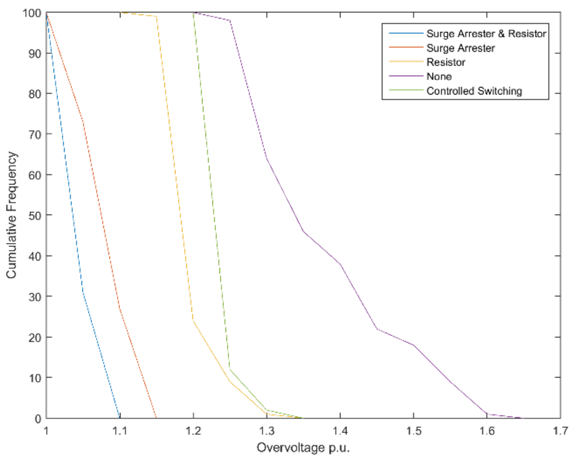

Figure 14. Statistical analysis of energization

The probability of the overvoltage due to energization is estimated by performing 100 experiments and approximated by Gaussian distribution. Cumulative frequency of occurrence is plotted against the overvoltage while considering the use of preinsertion of resistor, controlled switching, surge arester and a case where no mitigation method were investigated as shown in Fig. 14.

8. Conclusion

The use of harmonic filter on onshore substation of a wind farm is important to mitigate harmonic distortion, however the switching actions of the filter pose threat in form of temporary overvoltage to the system. Simulation of switching activities of harmonic filter on the onshore substation of a wind farm was performed using ATP/EMTP and the results can be summarized as follows:

- The overvoltage observed during energising is 1.53 P.U. and during de-energising is 2.67 P.U. The observed P.U is the resultant effect of the energization of the harmonic filter and the cable through which it was connected. The overvoltage experienced could have be propagated and rise above 1.53 P.U. by the travelling and reflection wave characteristic of the feeder cable. However, it was damped out by the shunt reactor also present on the onshore substation. The event of reclosing to a fault and de-energization was found to be critical and have potentials to cause stress to power equipment. In a case were the overvoltage experienced is found to be greater than the power frequency withstand level of the either the circuit breaker or the filter, which could lead to damage on them, hence mitigation methods are needed.

- For mitigation of energization, combination of pre-insertion resistor and surge arrester was proven to be most effective while controlled switching was found promising. The energy produced during the overvoltage is limited by using surge arrester and the pre-insertion resistor damped the magnitude of the overvoltage, hence the combined use of these two methods is potent for mitigating temporary overvoltage. These methods of mitigations would also reduce overvoltage during de-energization. However, they would not reduce overcurrent during reclosing to a fault, the surge accompanying this scenario is very severe and it chances of occurrence is very low.

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