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RESEARCH ARTICLE

Optimization-Based Mitigation Techniques of the Temporary Overvoltage in Large Offshore Wind Farm

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ABSTRACT Overvoltage transient is the major danger facing large offshore wind farms, as it may lead to a complete failure of the system components. A 150 MW offshore wind farm was modeled using the ATP-EMTP package to analyze the effect of the temporary overvoltage resulting from de-energization conditions, and the ferro resonance phenomenon resulting from the asymmetric opening of circuit breaker pole(s). The results showed that the best scenario to shut down such a system from the grid with minimum values of temporary overvoltage is to disconnect it, feeder, by a feeder. The stuck of one or more poles during the opening operation of the circuit breaker is a dangerous phenomenon, as it induces a high overvoltage value, which lasts for a long time causing more electric stress on the sensitive components of the system. The use of the Pre-Insertion Resistor PIR was recommended as a mitigation technique for the temporary overvoltage in large offshore wind farms, as it proves a significant reduction in the overvoltage values reaches to 79.44 % compared to surge arrester and shunt reactor which reduce the over voltage by 68.33%, 66.29% respectively. The genetic algorithm was used to find the optimum value of the PIR and shunt reactor that leads to the minimum TOV. The optimum value of PIR which was recorded is equal to 57.352 Ohm, which leads to more reduction in the overvoltage value by 9.67%. Also, the optimum values of the resistor and inductor of the shunt reactor were found to be 11.238 Ohms and 37.246 mH which leads to more reduction in the overvoltage value by 21.97% compared to the reduction without optimization.

INDEX TERMS Temporary overvoltage, overvoltage mitigation, ATP modeling, genetic algorithm optimization.

I. INTRODUCTION

Wind energy enjoys great importance in the whole world; offshore wind is a rapidly spread renewable energy technology that is expected to play an important role in future energy sources. In 2018, offshore wind provided a small share of the global electricity supply, but it is expected to expand strongly in the coming decades. The global offshore wind market increased nearly by 30% per year between 2010 and 2018 [1], [2].

Temporary overvoltage (TOV) is an oscillatory overvoltage last for a long period, ranging from seconds and can last for minutes, it has a slowly damped frequency that is close to or the same as the system power frequency [3]. TOV may happen because of a de-energization operation of the Circuit Breaker (CB) for maintenance or clearing a fault, and also from sudden load rejection, the energization of a transformer, the Ferranti effect in long transmission lines, inrush transient, and Fer resonance [4]. Temporary overvoltage (TOV) has a dangerous effect on power systems components, such as overheating of the transformer, and insulation failure due to the flashover. De-energization operations, which involve switching, may take place because of a system malfunction

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or the operator opening the circuit breaker. Additionally, a transmission line or an inductive load that is suddenly disconnected from the grid could cause it, leading to a spike in voltage [4], [5].

The overvoltage experienced on the system components may not me lead to instant damage, however, it might lead to mechanical stress, slow deterioration of the insulators to the point of flashover, and exhibiting the risk of the other types of transient overvoltage caused by lightning and switching operation [4], [5]. The impact of switching and temporary overvoltage with different types of transient events considered has been studied in [5]. Also, the temporary overvoltage due to load rejection considers the nonlinear behavior of the transformer, and the asymmetrical operations of the CB were studied in [6]. King et al. investigate the types of switching transients in a wind turbine farm, taking into consideration the level of overvoltage in both disconnected and connected faulted radial events [7]. Simultaneously energization of the parallel cables has been studied and the results showed that the more paralleled cables are energized at the same time, the higher voltage dip at the connecting bus occurs [8]. Han et al. investigated the effect of transient events on the overvoltage transient on two types of generators permanent magnet and squirrel cage [9]. Liljestrand et al. examined the transient events in a grid containing 80 wind turbines like the de-energization of the cables and different types of faults. In an offshore wind farm, Energization transients were studied When a radial system is energized, the overvoltage reaches over 2pu. The generated overvoltage was found to be lower when the radial system was energized when all the other systems were connected, and the rate of rise of the overvoltage at the WTT was doubled, it reaches 21kV/us. Also, the study shows that the transient events due to De-energization can generate higher values of overvoltage than energization transients. Finally, the study showed that if a circuit breaker disconnected a radial system in the case when the other wind turbines are still working in normal operation, the overvoltage reaches almost 5pu and if the circuit breaker disconnects a single phase to a ground fault when all the turbines are still working, the overvoltage reaches almost 7pu [10].

In this paper, considering the dangerous overvoltage values that happen due to the de-energization events, TOV due to the de-energization operations on an offshore wind farm is studied with the different scenarios of disconnecting the proposed farm from the grid. These scenarios include the shutdown of the farm by (1) disconnecting each wind turbine in each feeder, (2) disconnecting it feeder by feeder, and finally (3) disconnecting the whole wind farm by the main circuit breaker in the onshore substation. Studying the Ferranti effect, which causes a voltage increase along the cable because of the circuit breaker opening symmetrically. Also, the ferroresonance phenomenon due to the asymmetrical operations of the poles of the CB during de-energization is studied using ATP-EMTP software. Some mitigation techniques are proposed and use the ATP-EMTP software optimization tool to get the optimum values of the proposed mitigation techniques parameters.

II. SYSTEM MODELING AND DESCRIPTION

The layout of the offshore wind farm consisted of 30 wind turbines distributed in 6 feeders, each feeder has 5 turbines, under the present wind conditions, to reduce the aerodynamic losses between turbines, the optimal space between the turbines has been found to be 10–15D, where D is the turbine diameter. This large spacing between the turbines which reaches kilometers significantly increases the cost of transmission lines used. As a result, offshore wind farm designers have a complex multi-objective optimization problem which typically leads to operational turbine spacing of 6−10D [11]. The turbine used radius is 50m so the spacing is chosen to be 800m.

The generated wind turbine voltage is 0.69 kV and is stepped up by a 5 MVA 0.69/33 kV Wind Turbine Transformer (WTT). All turbines are connected through 6 submarine feeders to The MV bus.

The arrangement of the MV bus is a single bus bar that is sectionalized to get rid of a complete shutdown in case of repairs and maintenance. The two 150 MVA, 33/132 kV main transformers on the offshore substation, step the voltage up to 132 kV, and finally, transmit the power through submarine cables and then by land cable to the onshore substation Fig. 1.

The TOV under study might be categorized as a low-frequency transient that occurs between 0.1 to 3 kHz, according to a report provided in [12]. As a result, every significant part of the wind farm was modeled, considering the guidelines for low-frequency transients.

A. WIND TURBINE GENERATOR MODELING

The Doubly Fed Inducation Generator DFIG is widely used on wind turbines, it is preferred to be used than other types of generators. This is because they support effective power system dynamics since they are robust, allow for varying speeds, and can control both reactive and active power.

The DFIG model can be described by the following equations. As DFIG is a special type of induction generator so it has an equation that describes the stator voltage as shown in Eq. (1): [13]

$$\mathrm{V_s} = \mathrm{R_s I_s} + \frac{d}{dt\psi_\mathrm{s}} \tag{1}$$

where $\mathrm{V_s}$ and $\mathrm{I_s}$ are the stator voltages and currents, respectively, Rs and ψ_s represent the resistance and the flux linkages respectively.

The rotor flux is affected directly by stator flux according to Eq. (2), (3):

$$\Psi_\mathrm{r} = \frac{Lm}{Ls}\psi_\mathrm{s} + \sigma \mathrm{L_r I_r} \tag{2}$$

$$\sigma = 1 - \mathrm{L_m^2/L_s L_r} \tag{3}$$

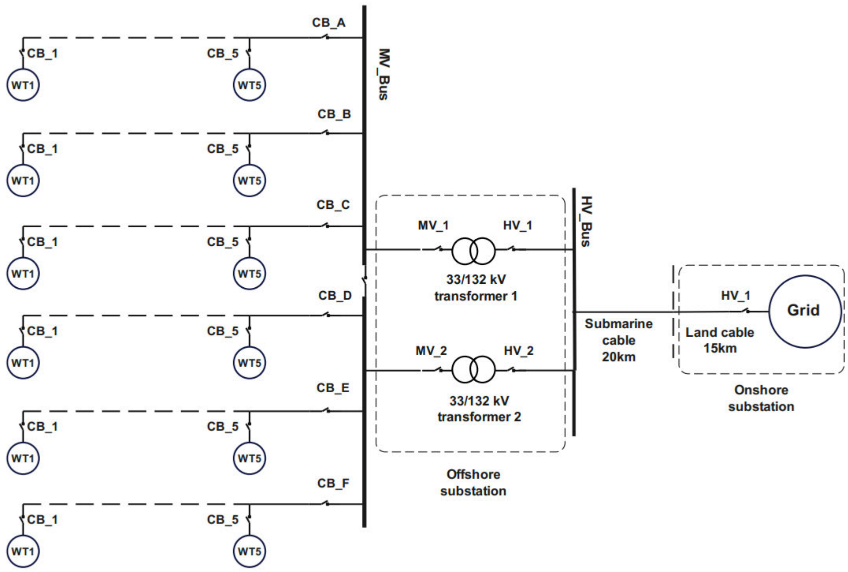

FIGURE 1. The offshore wind farm layout.

TABLE 1. Parameters of the DFIG.

Parameters	Values
Leakage Inductance of the rotor	0.033 mH
Resistance of the rotor	0.0073 Ω
Leakage Inductance of the stator	0.029 mH
Resistance of the stator	0.0023 Ω
Mutual inductance	0.8436 mH

where Ψ_r is the rotor flux, I_r is the rotor current, L_s, L_m, and L_r are the inductance of the stator, mutual inductance, and the rotor inductance respectively. σ is a factor that deals with the leakage flux effect between the stator and the rotor.

Also, the rotor terminal voltage can be calculated as shown in Eq (4):

$$V_r = \frac{Lm}{Ls}\frac{d}{dt}\psi_s + R_r I_r + \sigma L_r \frac{d}{dt} I_r \tag{4}$$

The first term describes the rotor-induce emf, and the second and third terms describe the effect of the rotor current on the resistance and inductance of the rotor.

In this paper, the DFIG is modeled using a universal machine (UM4) induction tool from the ATP/EMTP software [14]. The parameters of the DFIG wind turbine are shown in Table 1.

A simplified description of the DFIG is shown in Fig. 2.

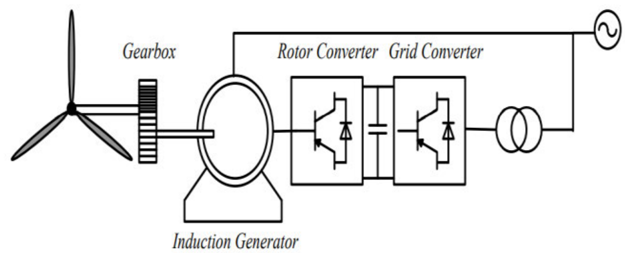

FIGURE 2. Simplified description of DFIG.

B. TRANSFORMER MODELING

The transformer is one of the most valuable components of a power system, and it is the most affected device against transients. To model a transformer in a transient simulation the effect of stray capacitances and nonlinear behavior must be considered.

TABLE 2. Modeling guideline for Representation Transformer Parameters.

Parameters	Low frequency Transients (0.1-3 kHz)	Slow front Transients (50/60to 3kHz)	Fast front transients (10 kHz to 3MHz	Very fast transients (100kHz to50MHz)
Short-circuit impedance	Very important	Very important	Important	Negligible
saturation	Very important	Very important	Negligible	Negligible
Iron losses	Important	Important	Negligible	Negligible
Eddy current	Very important	Important	Negligible	Negligible
Capacitive Coupling	Negligible	Important	Very important	Very important

Four categories are used to simulate electrical transients with frequencies ranging from dc to a few MHz as shown in Table 2, which is a modeling guideline developed by CIGRE [15]. This study falls under the category of low-frequency transient, transformer modeling was carried out in accordance with the guidelines in Table 2. When simulating transient overvoltage, the transformer's nonlinearity property is crucial.

The saturation effect due to the nonlinear behavior of the transformer's core has been externally modeled using element type 96. To do this, the external L_m option from the positive core magnetization tab is used. The representation of the core is done by using delta-connected three nonlinear inductors as shown in Fig. 3, which are connected externally at terminals of the BCTRAN model.

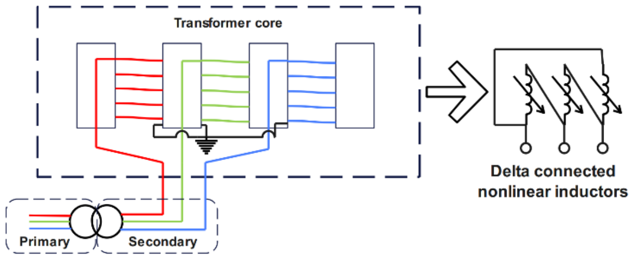

FIGURE 3. Modelling of the nonlinearity behavior of the transformer.

C. XLPE CABLE MODELING

Submarine cables are one of the most important electric components of offshore wind farms, the details are given for the submarine cable manufactured by ABB in Fig. 4 submarine cable cross-section. The frequency-dependent LCC model is used to represent the frequency dependence of single-core submarine cable parameters. The LCC model is highly recommended for electromagnetic transient studies.

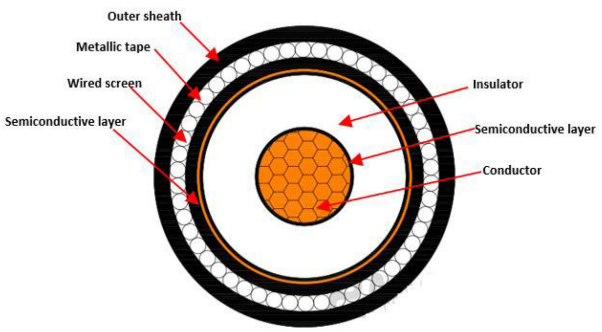

FIGURE 4. Submarine cable cross-section.

When thinking about temporary overvoltage, the cable's length is a crucial factor since it affects how the Ferranti effect works [16]. One wind turbine in a row is connected to another by an 800 m cable, and each row is connected by a 1000 m cable. Three 630 mm2 submarine cables, as well as land cables measuring 20 and 15 kilometers in length respectively, connect the offshore and onshore substation. The data for these cables were taken from the manufacturer's data sheet [17]. The selected cable details are shown in Table. 3.

TABLE 3. ABB XLPE submarine cable data.

Parameter	Value
Cross section of the conductor (mm2)	630
Diameter of the conductor (mm)	29.8
Insulation thickness (mm)	23.0
Diameter over insulation (mm)	79.5
Lead sheath thickness (mm2)	3.0
Outer diameter of cable (mm)	224.0
Cable weight (Copper) (kg/m)	86.7
Capacitance (μF/km)	0.16
Charging current per phase at 50 Hz (A/km)	6.4

III. TOV DUE TO THE DIFFERENT DE-ENERGIZATION SCENARIOS

In this section, the different de-energization scenarios of the offshore wind farm will be investigated to find the corresponding TOVs.

A. DE-ENERGIZATION OF ONE WIND TURBINE AT ANY FEEDER

By simultaneously opening the three poles of the circuit breaker, one wind turbine transformer on a feeder is de-energized to disconnect one of the wind turbines while the others stay closed.

The Ferranti effect is frequent due to the disconnecting operations at a long transmission line receiving end, but it can also happen in the case of a short cable due to its high surge impedance. this is the cause of the overvoltage when one WTT in a feeder is de-energized.

The wind turbine 1 (WT 1) is de-energized by CB_1 due to maintenance operations or fault clearing, opening all the poles of the circuit breaker at 0.7283s when the voltage of phase A is at its peak to get the maximum possible overvoltage. Fig. 5 shows the primary and secondary sides voltage of the WTT 1. An overvoltage of 4.26 and 5.4 pu was observed at the primary and secondary sides respectively, which damps to the steady state after a period of 2.5 s.

The de-energization effect of the CB_1 on the other wind turbines was examined it reached 1.66, 1.56, 1.42, and 1.2 pu respectively at the other four WT as shown in Fig. 6.

B. DE-ENERGIZATION OF ONE FEEDER CONNECTED TO THE MV BUS

The circuit breaker CB_A was disconnected at 0.7238 s at the peak value of phase A and the other wind turbines were still working. It is observed that the overvoltage generated on all the WTTs of feeder A is the same as shown in Fig. 7.

The overvoltage is almost the same as that appears in the previous section the only difference is the overvoltage appears on all the WT connected to the feeder. The overvoltage on all the other feeders was examined and the results show that these feeders are not affected.

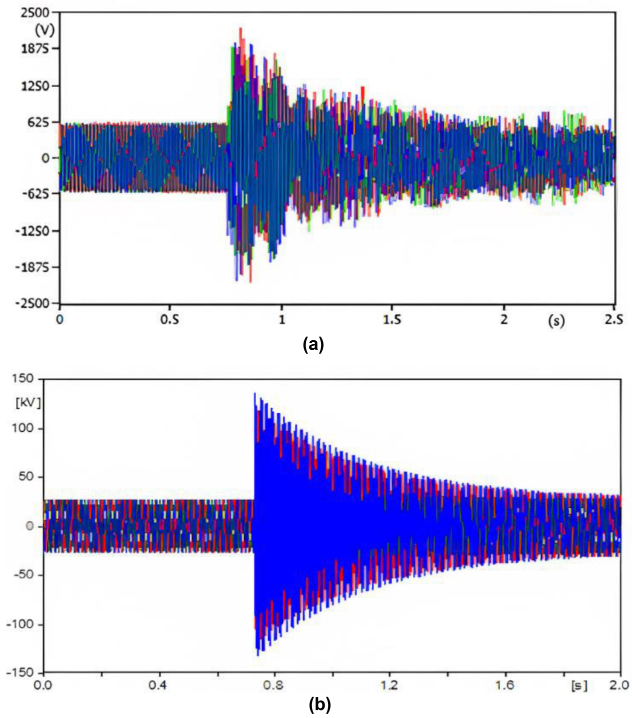

FIGURE 5. Overvoltage at the WTT sides due to the symmetrical opening of the poles a) primary side; (b) secondary side.

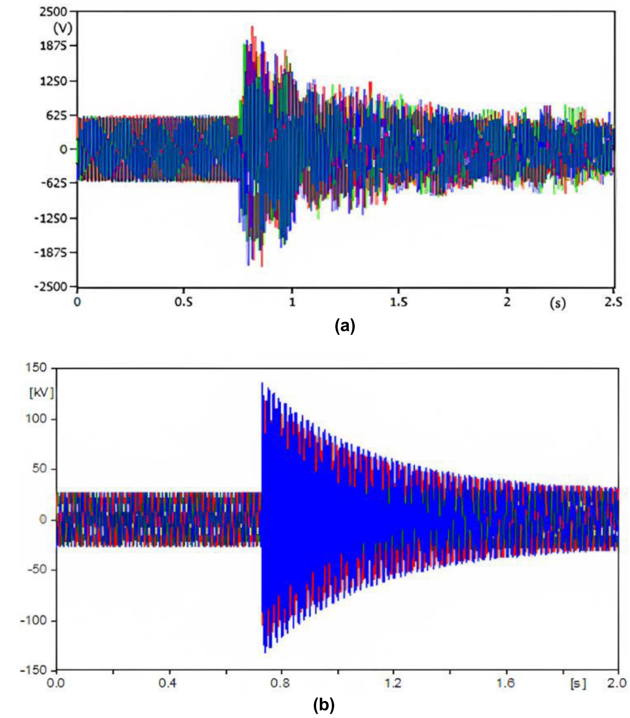

FIGURE 7. The overvoltage at the WTT sides of all the wind turbines connected to feeder A opening 3-poles simultaneously. (a) primary side; (b) secondary side.

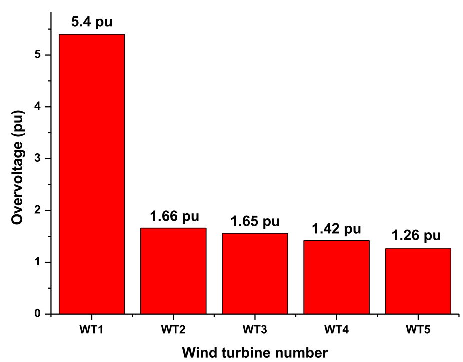

FIGURE 6. The maximum overvoltage appears at the secondary side of the five WT in the first feeder in pu.

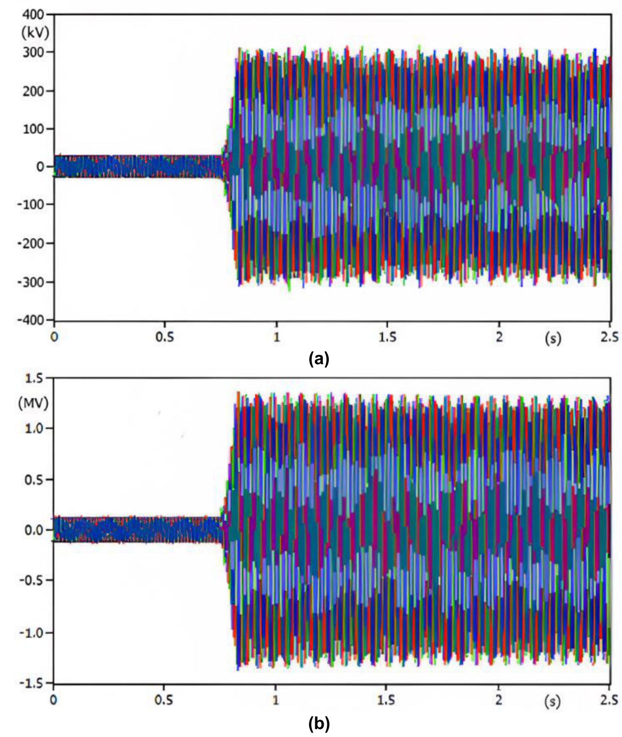

FIGURE 8. The main transformer overvoltage due to disconnecting of the CB_SUB (a) primary side; (b) secondary side.

C. DE_ENERGIZATION OF THE WHOLE OFFSHORE WIND FARM

A complete shutdown of the offshore wind farm is examined by disconnection of the CB_SUB at the onshore substation to disconnect the farm from the grid. This case shows a huge overvoltage value.

An overvoltage of 11.11 pu and 11.56 pu at the primary and secondary side respectively During the symmetrical opening of the breaker, this overvoltage was experienced by all the wind turbines as shown in Fig. 8.

It can be concluded from the results shown that it is not a preferred scenario to shut down the farm from the grid by disconnecting the circuit breaker at the onshore substation (CB_SUB) because it generates a very high value on all

WTT which can damage them. The preferred scenario is to disconnect the incoming feeder one by one to disconnect the farm from the grid.

IV. TOVs DUE TO FERRO RESONANCE PHENOMENA

During the de-energization of the circuit breaker, an abnormal operation can occur. This abnormal operation such as two of the poles are stuck and the remaining one is opened. The same ferro resonance phenomenon would occur if one pole was stuck because of the interaction of the submarine cable's stray capacitance and the WTT's inductance [16].

A. OVERVOLTAGE WHEN TWO POLES OF THE CIRCUIT BREAKER ARE STUCK

The overvoltage experience on the 33 kV side of the WTT because of the opening of only one pole is examined when disconnecting only one turbine in a feeder by opening the circuit breaker CB_1 and when disconnecting the whole feeder by opening the circuit breaker CB_A. The results show that the overvoltage is almost the same in the two cases it reaches 1.19 pu as shown in Fig. 9.

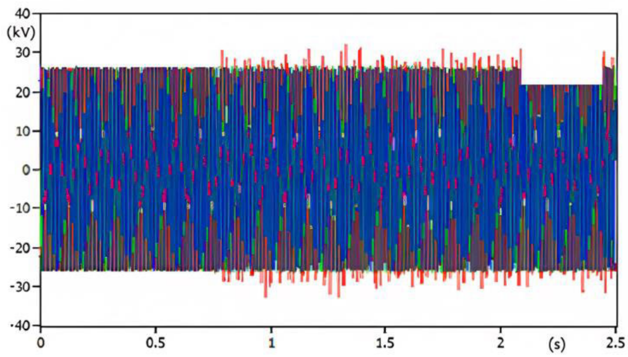

FIGURE 9. WTT overvoltage caused when two poles stuck While disconnecting one turbine in a feeder, or disconnecting the whole feeder.

B. OVERVOLTAGE WHEN ONE POLE OF THE CIRCUIT BREAKER IS STUCK

The stuck of only one pole During the de-energization operation can lead to the same ferro resonance phenomena, to carry out this event, the circuit breaker CB_1 and CB_A were de-energized with two poles being opened. The overvoltage experience on the 33kV side of the WTT because of the opening of only one pole is examined. the results show that the overvoltage is almost the same in the two cases it reaches 3.3 pu as shown in Fig. 10.

C. OPENING OF THE DISCONNECTOR

The arrangement of the MV bus is a single bus bar that is sectionalized to get rid of a complete shutdown in case of repairs and maintenance. To simulate this scenario the circuit breaker of the main transformer 2 (CB_HV 2) is opened and at 0.75 s the disconnector between feeders C and D is opened.

The results show an overvoltage at the main transformer 1 reaches 1.48 and 1.61 pu at the primary and secondary side

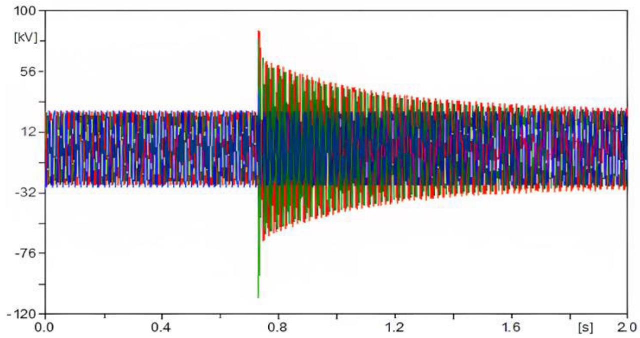

FIGURE 10. Overvoltage at the WTT caused when one pole stuck. while disconnecting one turbine in a feeder, or disconnecting the whole feeder.

respectively Fig.11. This is because of the ferro resonance effect This occurred because of the interaction of the transformer's nonlinear inductance and stray capacitance on the line and bus bar [16].

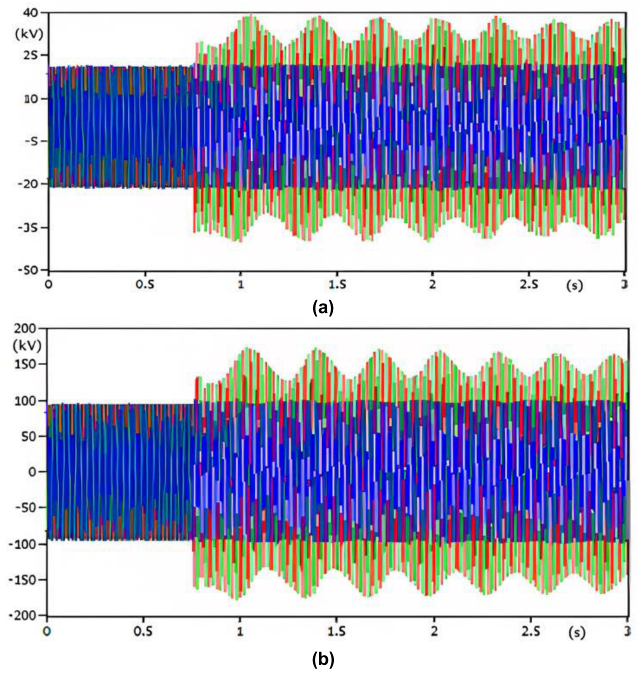

FIGURE 11. The main transformer 1 overvoltage due to while opening the disconnector (a) at the primary side, (b) at the secondary side.

Also, the overvoltage values last for long period, it lasts for all the simulation time of 3s, this long period maximizes the drawbacks that could be occurred due to this temporary overvoltage.

It can be concluded from the results shown in the previous section that the TOVs due to the ferro resonance phenomena is dangerous to the system component, it reaches a high value and lasts for long period enough to harm the system, but the opening of the three poles simultaneously simulates the worst-case scenario.

Table 4 summarized the overvoltage values in pu due to different cases of opening the circuit breaker, so these values

TABLE 4. overvoltage values in pu due to different cases of opening the circuit breaker.

Opening CB_1	TOV on the high voltage side of WTT in pu
Three poles simultaneously	5.4
Two poles are stuck	1.19
One pole is stuck	3.3

is used as a reference to mitigate them using the mitigation techniques proposed in the following section.

V. MITIGATION OF THE TEMPORARY OVERVOLTAGE

It can be concluded from the results shown in the previous sections that the overvoltage reaches high values enough to damage the sensitive component of the wind turbine, especially when these values exceeded the rated basic insulation level (BIL).

Almost all the overvoltage values investigated in this study are above the tolerable temporary overvoltage value, which is 2 pu, so it must be mitigated [3].

A. THE PRE-INSERTION RESISTOR (PIR)

The Pre-Insertion Resistance PIR is a mitigation technique that uses a damping resistor connected in series with the cable and short-circuited normally after 10ms to reduce and the overvoltage value that appears on the system sensitive points. [18].

The PIR used for the mitigation purpose is equal to 38.7 Ohms which is calculated using Eq (5):

$$\mathrm{PIR} = \frac{3\sqrt{3}V_n^2}{P_e} \tag{5}$$

where V_n is the rated voltage of the transformer and P_e is the maximum power, a transformer can operate at without experiencing an excessive temperature rise.

The PIR effect on the overvoltage values at the primary and secondary sides of the WTT is examined when opening the 3-poles of the circuit breaker simultaneously which simulate the worst-case scenario. Fig. 12 shows that the overvoltage value at the primary side is reduced to 1.24 pu compared to 4.26 pu before using the PIR. Also, the peak value at the secondary side reduces to 1.11 pu compared to 5.4 pu, All the values become under 2 pu which is the tolerable TOV.

B. THE SURGE ARRESTER

Surge arresters can be represented by different models including Pinceti, Fernandez, and the institute of electrical and electronics engineers (IEEE) model. The model of surge arrester used in this study is the IEEE model, The data used to model the arrester and the V-I characteristics of the surge arrestors were obtained according to the manufacturer data sheet and the IEEE/ANSI C62.11-1993 standard [19], [20].

The effect of using the surge arrestor on the TOV values at the primary and secondary sides of the WTT is examined when opening the 3-poles of the circuit breaker simultaneously.

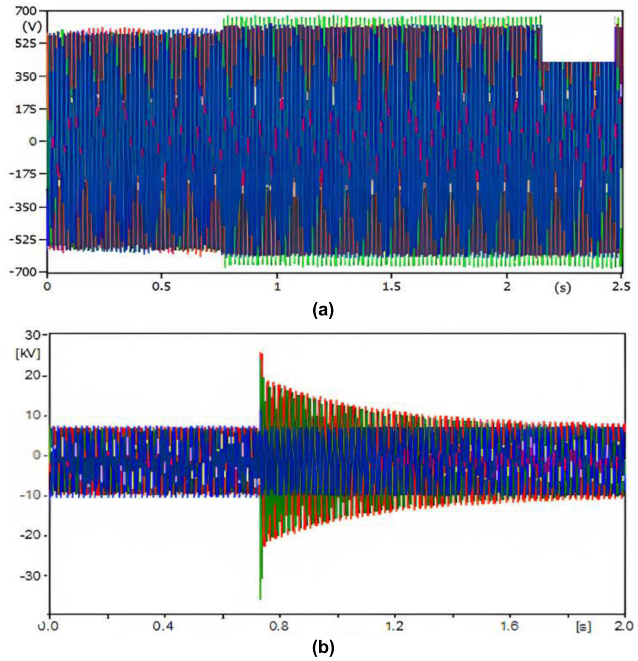

FIGURE 12. The effect of using the PIR on the overvoltage values at WTT (a)at the primary side, (b) at the secondary side.

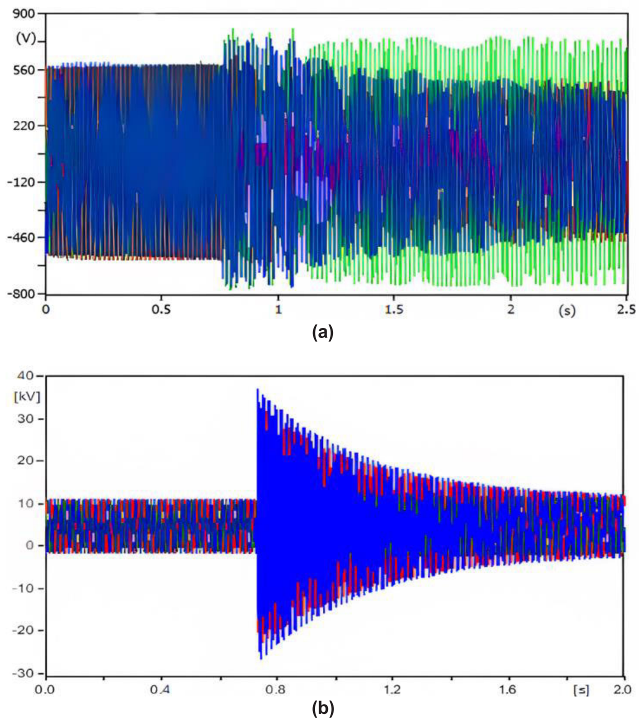

FIGURE 13. The Effect of using the surge arrester on the overvoltage values at WTT(a)at the primary side, (b) at the secondary side.

Fig. 13 shows that the overvoltage value at the primary side is reduced to 1.53 pu compared to 4.26 pu before using

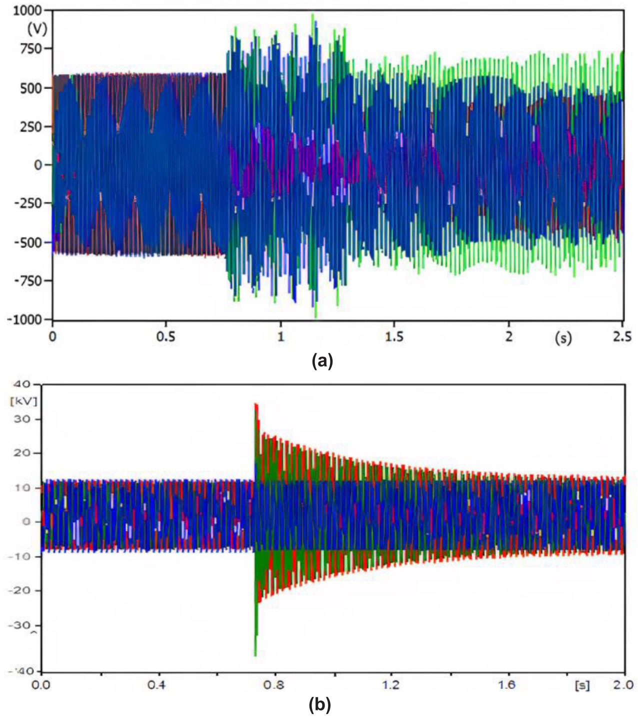

FIGURE 14. **The Effect of using the shunt reactor on the overvoltage values at WTT At the primary side, (b) at the secondary side.**

the surge arrestor. Also, the peak value at the secondary side reduces to 1.71 pu compared to 5.4 pu, all the values become under 2 pu which is the tolerable TOV.

C. THE SHUNT REACTOR

The shunt rector is one of the common mitigation techniques used to reduce the effect of transient overvoltage such as TOV. The shunt reactor is an R-L branch connected close to the transformer modeled by a lumped inductor with a serious resistance sometimes a parallel resistance added to get high-frequency damping [21], the reactor values are calculated using the equations (6-7): [16]

$$R = \frac{1}{\omega C} \tag{6}$$

$$L = \frac{1}{\omega^2 C} \tag{7}$$

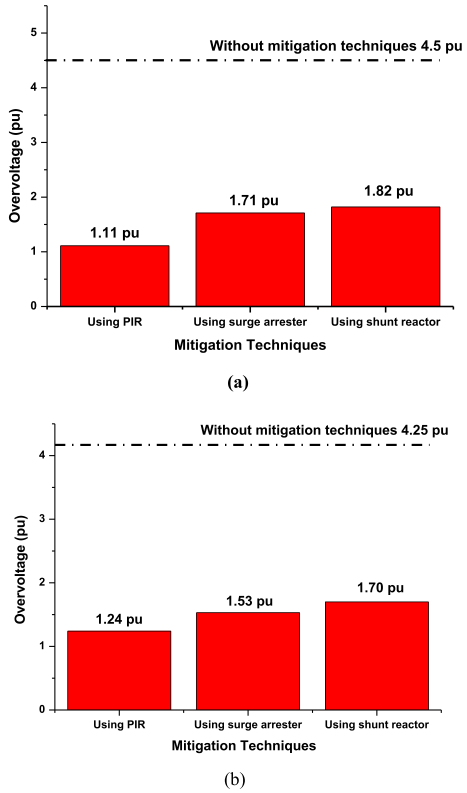

FIGURE 15. **Comparison between the overvoltage values after and before using the mitigation(a) at the primary side, (b) at the secondary side.**

where ω is the angular frequency and C is the stray capacitance that appears at the transformer terminals. The effect of using the shunt reactor on the TOV values at the primary and secondary sides of the WTT is examined when opening the 3-poles of the circuit breaker simultaneously. Fig. 14 shows that the overvoltage value at the primary side is reduced to 1.7 pu compared to 4.26 pu before using the surge arrestor. Also, the peak value at the secondary side reduces to 1.82 pu compared to 5.4 pu, All the values become under 2 pu which is the tolerable TOV.

The results discussed in the previous sections are summarized in Table 5, the PIR simulates the best method as it reduces the TOV value to 1.24 pu and 1.11 pu compared to the original values of 4.26 and 5.4 at the primary and secondary sides of the WTT respectively. Fig. 15 describes

TABLE 5. **Comparison between the three mitigation techniques.**

TOV values	At the primary side (pu)	Percentage of reduction	At the secondary side (pu)	Percentage of reduction
Without mitigation	4.26	0 %	5.4	0%
Using PIR	1.24	70.9 %	1.11	79.44 %
Using surge arrester	1.53	64.08 %	1.71	68.33 %
Using shunt reactor	1.7	60.09 %	1.82	66.29 %

TABLE 6. The optimum value of PIR using genetic algorithm.

Variable	Minimum	Maximum	Best fit
PIR (Ω)	1	75	57.352

TABLE 7. The optimum value of Shunt reactor using genetic algorithm.

Variable	Minimum	Maximum	Best fit
R (Ω)	1	20	11.238
L (mH)	10	100	37.246

this comparison as it is obvious that the best method is to use the PIR, then using the surge arrester, and finally the shunt reactor.

VI. OPTIMUM VALUES FOR THE MITIGATION TECHNIQUES UNDER STUDY

MODEL Write Max/Min in the EMTP-ATP software is used to obtain the optimum values of the PIR and the shunt reactors are used to maximize their effect on the mitigation of the TOV. This model uses different optimization routines such as The Gradient Method (GM), The Genetic Algorithm (GA), and The Simplex Annealing (SA) method.

A. OPTIMUM VALUE OF THE PIR

In this study, the genetic algorithm is used. the population and the maximum iteration are set to 50, these values could be larger to get more accurate results, but the simulation time will be so long. Also using the GA required minimum and maximum values to be given to the model, these values are set to 1 and 75 respectively.

The results show that the value of the PIR that has the minimum TOV is 57.352 Ohms as shown in Table 6. use this value to get the corresponding TOV, it is found to be 1.12 and 1.06 pu at the primary and secondary sides respectively.

It is important to mention that, although this value of PIR reduces the TOV generated, according to equation (5), this increase in the PIR value will lead to a decrease in the maximum power the transformer can work at without an excessive rise in temperature. So, this must be taken into consideration when choosing the WTT specification and while designing the thermal protection of the transformer.

B. OPTIMUM VALUE OF THE SHUNT REACTOR

In this case the shunt reactor has to variables, the series resistance R and the inductor L.

The population and the maximum iteration are set to 50 to decrease the simulation time, and the minimum and maximum values of the resistance and inductor are set to be 1 to 20 Ohms for the resistance and 10 to 100 mH for the inductor.

The results in Table 7 show that the optimum value of the resistance and the inductor that has the minimum TOV is 11.238 Ohms and 37.246 mH as shown in Table 7. use this value to get the corresponding TOV it is found to be 1.37 and 1.42 pu at the primary and secondary sides respectively. Table 8 summarizes the effect of using PIR and shunt reactor before and after optimization.

VII. CONCLUSION

An ATP-EMTP program package is used to model the transient status of the 150MW, grid–connected offshore wind farm, and the temporary overvoltage due to some de-energization scenarios are examined. Also, three mitigation techniques are used to reduce the TOV obtained. Finally, the genetic algorithm technique is used to optimize the mitigation technique parameters to reach the minimum TOV. The following main points can be concluded from this study:

1- TOV of 4.26 was generated at WTT primary side when the circuit breakers poles are opened simultaneously also, 1.08, and 4.17 pu were generated at the same point when two and one poles were stuck during de-energization respectively.

2-TOV of 5.4 was generated at WTT secondary side when the circuit breakers poles are opened simultaneously also, 1.19, and 3.3 pu were generated at the same point when two and one poles stuck during de-energization respectively. This overvoltage last during the simulation time of 2.5s.

3-Only the de-energized WT is significantly affected by this overvoltage, the other four turbines experienced an overvoltage of 1.66, 1.56, 1.42, 1.26 pu respectively.

TABLE 8. The TOV before and after using the optimization techniques.

TOV values	At the primary side			At the secondary side		
	Before optimization (pu)	After optimization (pu)	Percentage of reduction	Before optimization (pu)	After optimization (pu)	Percentage of reduction
Using PIR	1.24	1.12	9.67 %	1.11	1.06	4.5%
Using shunt reactor	1.7	1.37	19.41%	1.82	1.42	21.97%

4-De-energization of one feeder leads to an overvoltage almost the same as that appears when opening the circuit breaker of one WT, the only difference is the overvoltage appears on all the WT connected to that feeder. Also, the overvoltage on all the other feeders was examined and the results show that these feeders are not affected.

5-Althoug the De-energization of the disconnector leads to low overvoltage at the main transformer 1 reaching 1.48 and 1.61 pu at the primary and secondary sides respectively, its danger lies in the long time for which it last in the system as it lasts for all the simulation time of 3 sec.

6-It is not a preferred scenario to shut down the farm from the grid by disconnecting the circuit breaker at the onshore substation (CB_SUB) because it generates a very high value of 11.11 pu and 11.56 pu at the primary and secondary sides on all WTT respectively. These values can damage the turbine. The preferred scenario is to disconnect the incoming feeder one by one and then disconnect the farm from the grid.

7-Using the PIR, surge arrestor, and shunt reactor the TOV value is reduced to 1.24, 1.54, and 1.7 pu at the primary side of the WTT respectively compared to 4.26 pu before mitigation. Also, these values reduced to 1.11, 1.71, and 1.82 pu at the secondary side respectively compared to 5.4 pu before mitigation. So, it can be concluded that The PIR is the best mitigation technique used, then the surge arrester, and finally the shunt reactor.

8-The Genetic algorithm is used to find the optimum value of the PIR and shunt reactor that leads to the minimum TOV. the results show that the optimum value of PIR=57.352 Ohm leads to more reduction in the overvoltage value by 9.67%. Also, the optimum values of the shunt reactor R=11.238 Ohms and L=37.246 mH leads to more reduction in the overvoltage value by 21.97% compared to the reduction before optimization.

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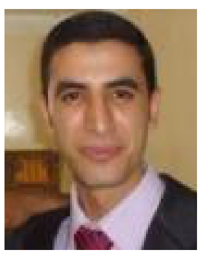

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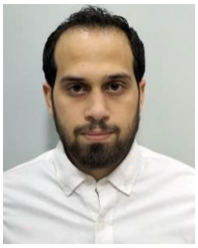

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