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A Hidden Markov Model Algorithm For Insulation Co-Ordination Of Power System Equipment

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Abstract: *The demand for the generation and transmission of large amounts of electric power today, necessitates its transmission at extra-high voltages. The diverse conditions under which a high voltage apparatus is used make it very crucial that careful design of its insulation and the electrostatic field profiles are maintained. Insulation coordination addresses the above demand. Transient models used by other researchers are inaccurate due to deterministic approaches used, which arenot flexible and comprehensive. In this paper a stochastic model known as the Hidden markovmodel (HMM) has been used to solve this problem. Modelinga lightning induced overvoltage in a high voltage power system and MATLAB/SIMULINK software were used successfully to obtain good results for the insulation procedure. Therefore, from the maximum likelihood signal obtained from the HMM, it was discovered that relocating the Arrester placement to within 5.56m of the transformer will achieve a protection margin of 18% which is more than the minimum required standard margin of protection of 15%.*

Keywords*: Insulation Coordination, Hidden Markov Model, Basil Insulation Level(BIL),Margin of Protection, Lightning.*

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I. Introduction

Over voltages are phenomena which occur in power system networks either externally or internally. The selection of certain levels of over voltages which are based on equipment strength for operation is known as insulation coordination**[1]**. In power systems, it is essential for electrical power engineers to reduce the number of outages and preserve the continuity of service and electric supply. In another perspective, insulation coordination is a discipline aiming at achieving the best possible techno-economic compromise for protection of persons and equipment against over voltages, whether caused by switching actions in the network or lightning, occurring on electrical installations. The purpose of insulation coordination is to determine the necessary and sufficient insulation characteristics of the various network components in order to obtain uniform withstand to normal voltages and to over voltages of various origins.

However, over voltages are extremely hard to calculate. They cannot generally be predetermined, since they involve incalculable elements which vary from site to site. Hence effective insulation coordination requires accurate modeling of the power system. Modeling transmission lines and substations helps engineers understand how protection systems behave during disturbances and faults.

Though a number of techniques have been developed for modeling transient disturbances in power systems, the problem of achieving optimal insulation coordination is still limited by accurate model of the power system. Generally, for existing insulation coordination studies, the power system has been modeled either by deterministic mathematical techniques or by statistical methods. The shortcoming of the existing conventional mathematical technique of insulation coordination analysis is that it assumes that the power system dynamics is linear. This makes analysis of over voltage response of the system under transients less optimal for determining over voltage withstand of system elements. Also the statistical technique, though more accurate**[2][3][4]** is known that the statistical evaluation of the risk cannot be assessed if the breakdown behavior of the insulation is unknown or if it is referred only to the basic impulse level(BIL) of the power system component. Hence an algorithm for insulation coordination procedure for power system equipment is proposed in this work.

II. The Hidden Markov Model

Hidden Markov Models (HMMs) are learnable finite stochastic automates. Nowadays, they are considered as a specific form of dynamic Bayesian networks. Dynamic Bayesian networks are based on the theory of Bayes**[5]**.

A Hidden Markov Model consists of two stochastic processes. The first stochastic process is a Markov chain that is characterized by states and transition probabilities. The states of the chain are externally not visible, therefore "hidden". The secondstochastic process produces emissions observable at each moment, depending on

a state-dependent probability distribution. It is important to notice that the denomination “hidden” while defining a Hidden Markov Model refers to the states of the Markov chain, not to the parameters of the model.
The history of the HMMs consists of two parts. On the one hand there is the history of Markov process and Markov chains, and on the other hand there is the history of algorithms needed to develop Hidden Markov Models in order to solve problems in the modern applied sciences by using for example a computer or similar electronic devices**[5]**.

2.1 MODEL DESIGN EQUATIONS/STRATEGY

The summary of the highlights of the model design strategy of this work, for the insulation coordination of a power station is given with the classification ability of Hidden Markov Model(HMM). This is used to identify the travelling wave structure that exhibits the highest likelihood probability on the power system under investigation. This identified transient wave model is used to compute for the insulation coordination of the power system based on the IS/IEC 60071-2 guidelines and standard and application of MATLAB/SIMULINK.

2.2. The Overvoltage Training Disturbance Classification

The proposed hidden markov model, classifies the destructive impact of the lightning induced overvoltage transient on the power system, by comparing the maximum likelihood probability of the overvoltage signal for trained models. A HMM model is trained for each of the three overvoltage transient disturbance scenarios identified earlier on.
A HMM is defined as λ = (N, M, π, A, B), where N is the number of states, M is the number of distinct observation symbols per state, π and B is the initial state distribution probability and observation probability matrices respectively. The elements of matrix A, a_{ij}, is the transition probability from state i to state j, which are defined in equations (1) and (2) **[6]** in these equations, q_t is the actual state S at time t.

$$a_{ij} = P[q_{t+1} = S_j | q_t = S_i],\ 1 \leq i,\ j \leq N \quad (1)$$

$$a_{ij} \geq 0,\ \sum_{j=1}^{N} a_{ij} = 1 \quad (2)$$

The elements of matrix B, b_j(k), are defined by equation (3) where V_k is the K^{th}observation in the state matrix B and vector π elements follow the rules presented in equation (4) **[6]**

$$b_j(k) = P[(O_t = V_k | q_t = S_j)],\ 1 \leq j \leq N,\ 1 \leq k \leq M \quad (3)$$

$$b_j(k) \geq 0, \sum_{k=1}^{M} b_j(k) = 1, \sum_{i=1}^{N} \pi_1 = 1) \quad (4)$$

Where O_t indicates observation at time t. Equation (3) calculates the probability of observation V_k at time t, where $q_t = S_j$.
The HMM training process is identical to finding the appropriate parameters of A, B and π. For convenience the HMM is denoted as a triplet:

λ = (A, B, π).

This work uses the MATLAB software environment. The modeling of the case study power system in MATLAB enables the extraction of electrical features of the disturbance wave system. The features in Table 1 are selected from candidate feature set from the overvoltage transient features.
Equation (5) is utilized by the MATLAB to implement this**[7]**.
Program/formula used to calculate the dynamic volume under different disturbances is.

$$W_x = \frac{\Delta W}{W_0} \times 100\% = \frac{W_1 - W_0}{W_0} \times 100\% \quad (5)$$

$W_0$is the basic value before the disturbances,
$W_1$is the value under disturbances, and W_x describes the relative sensitivity.
If the $|W_x|$≥ 100%, this feature would be selected.
Thus, the flow chart of the proposed algorithm for the novel Insulation Coordination procedure is shown in Figure1.

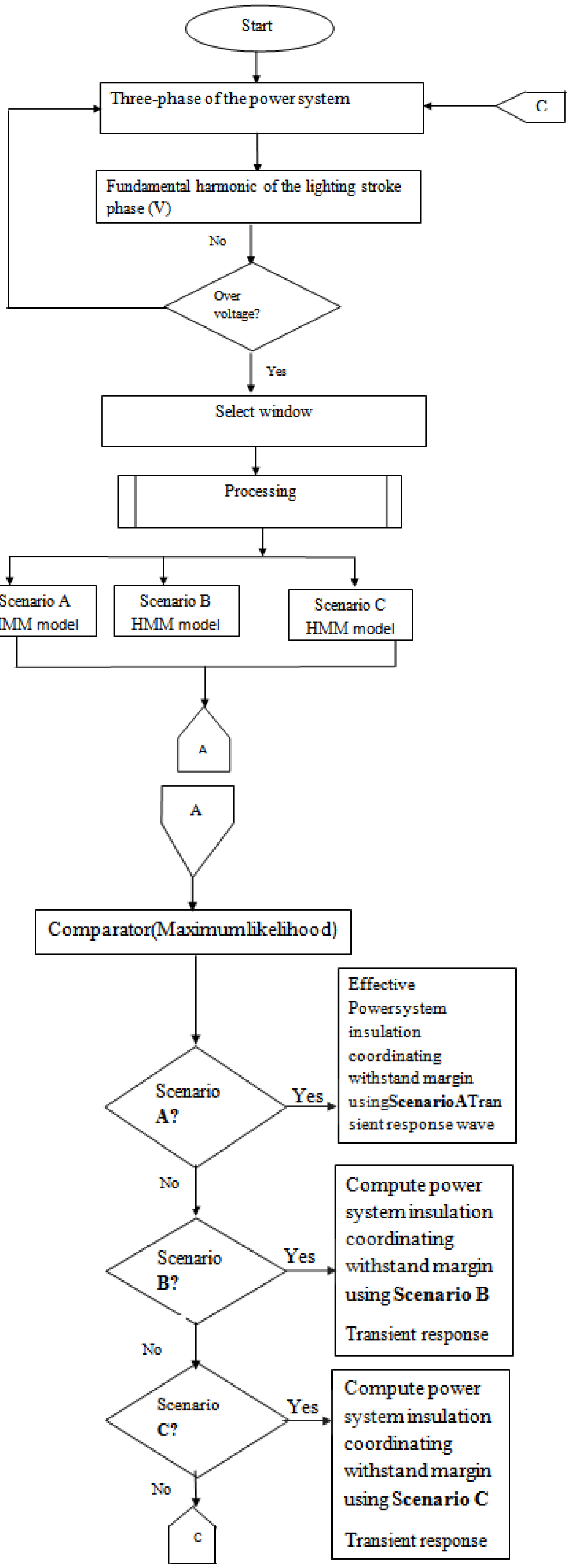


Figure1 Flowchart/Algorithm for the novel insulation coordination procedure.

III. Modelling Of The Power Station

The 330/132kV substation at New Haven, Enugu, Nigeria was used to evaluate the proposed algorithm forthe insulation coordination technique. The time domain simulation carried out with MATLAB, is used to assess (based on the HMM identified maximum likelihood) whether the combination of surge arrester and their location with respect to the transformer provide adequate margin of protection.The substation is modeled in MATLAB/Simulink, using drawings supplied by Power Holding Company of Nigeria (PHCN) Transmission station. The voltage values at a chosen arrester protection zone in the station, is determined with a simulated lightning surge entering the station from the incoming line. Three (3) lightning surge disturbance scenarios are observed by the HMM algorithm. From the training of these three transient disturbance model (using about n iterations), HMM identifies from among the surge signals, a waveform structure having the maximum likelihood at location of the substation being investigated. The identified maximum likelihood wave is used to calculate the protection margin based on equipment data supplied by PHCN.

The MATLAB/Simulink model of the power system is given in Figure 2. The MATLAB m-file source codes that implement the HMM algorithm were written. Also the single line diagram of the station is in Figure 3. In simulation studies, the lightning flash is substituted with impulse current generator. Impulse generator (IG) generates very steep-front wave shapes, known as impulse waves, that are similar to lightning waves**[8].**

For the simulation carried out in this chapter, impulse current waveforms have been generated in the MATLAB. This is provided by the lightning impulse current source in the model of figure 2. A lightning current wave of 30KA is injected into the phase conductors and propagated into the system during operation. The 132/33KV New Haven Power Transmission Station Parameters/data used in this work are shown in Table 1.

It is important to note that the steepness of the incoming surge into a station is a crucial factor on how well the arresters are able to protect the equipment at the station.

The steepness S of the surge is given by**[9];**

$$S = \frac{1}{K_{co}X_T} \qquad (6)$$

Where $$X_T = \frac{X_p}{4} \qquad (7)$$

$$X_p = \frac{2T}{[nK_{co}(U - U_{pl})]} \qquad (8)$$

Where K_{co} is the corona damping constant according toTable 1:

X_p is the limit overhead line distance within which lightning events have to be considered(m).

n is the number of overhead lines connected to the substation.

T is the longest travel time between the point to be protected and the closest arrester (μs).

U_{pl} is the lightning impulse protective level of the arrester.

U is the considered overvoltage amplitude.

A Simulink model of the 132/33kVPower transmission station located at Hew Haven, Enugu, Nigeria is shown in Figure 2.

Table 1: Station Parameters/Data supplied by PHCN

S/N	PARAMETERS	VALUES
1	Transformer BIL	850V
2	Arrester BIL, E_a or U_{pl}	650V
3	Surge Impedance of Line	400Ω
4	Arrester-Transformer Separation distance	6.5m
5	Ground Clearance	6.10m
6	Vertical distance between conductors	3.96m
7	Horizontal Space between conductors	7.0m
8	Mid-Span clearance	6.1m
9	Vertical distance from overhead conductor to Arrester, a_1	2m
10	Active length of Arrester, a_4	3.6m
11	Vertical distance of Arrester conductor to earth, a_2	15m
12	Length of Phase conductor between Arrester and Protected equipment, a_3	6.5m
13	No. of lines per circuit	2
14	Travelling wave velocity	300m/μs
15	Rated Frequency	50Hz
16	Steady state voltage	132KV

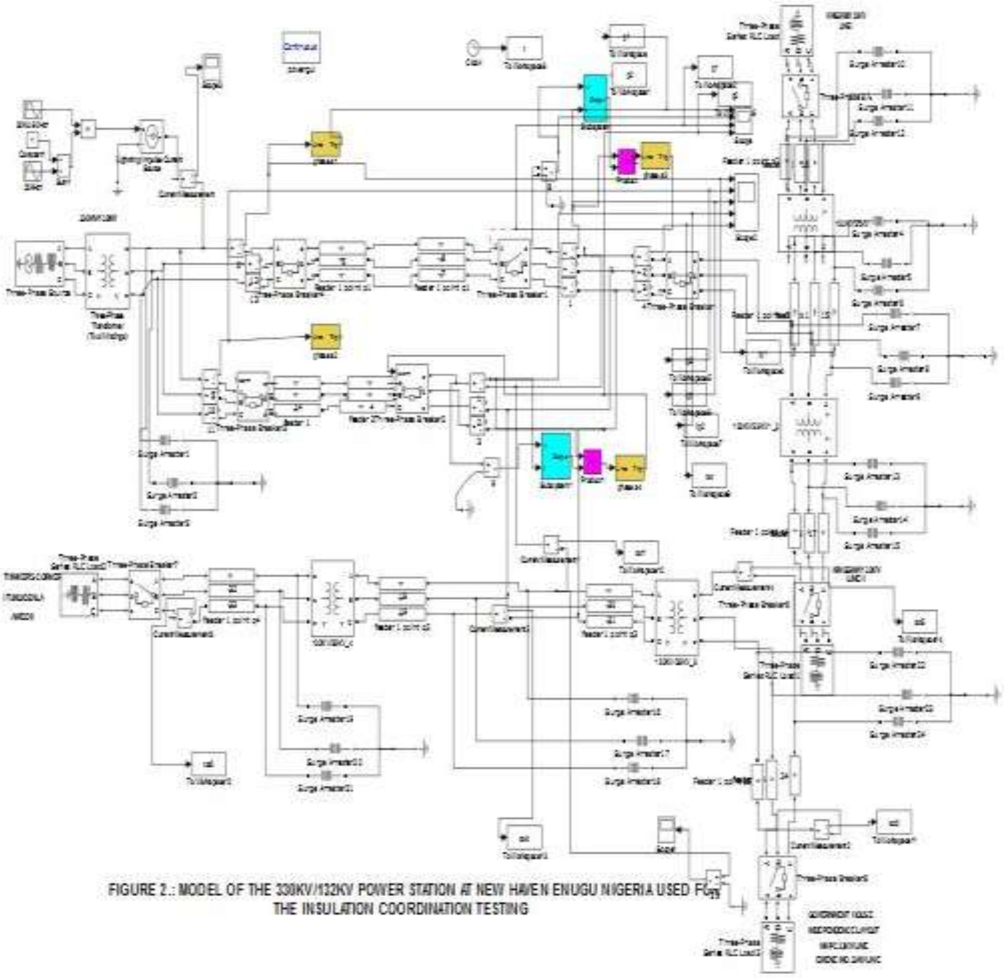
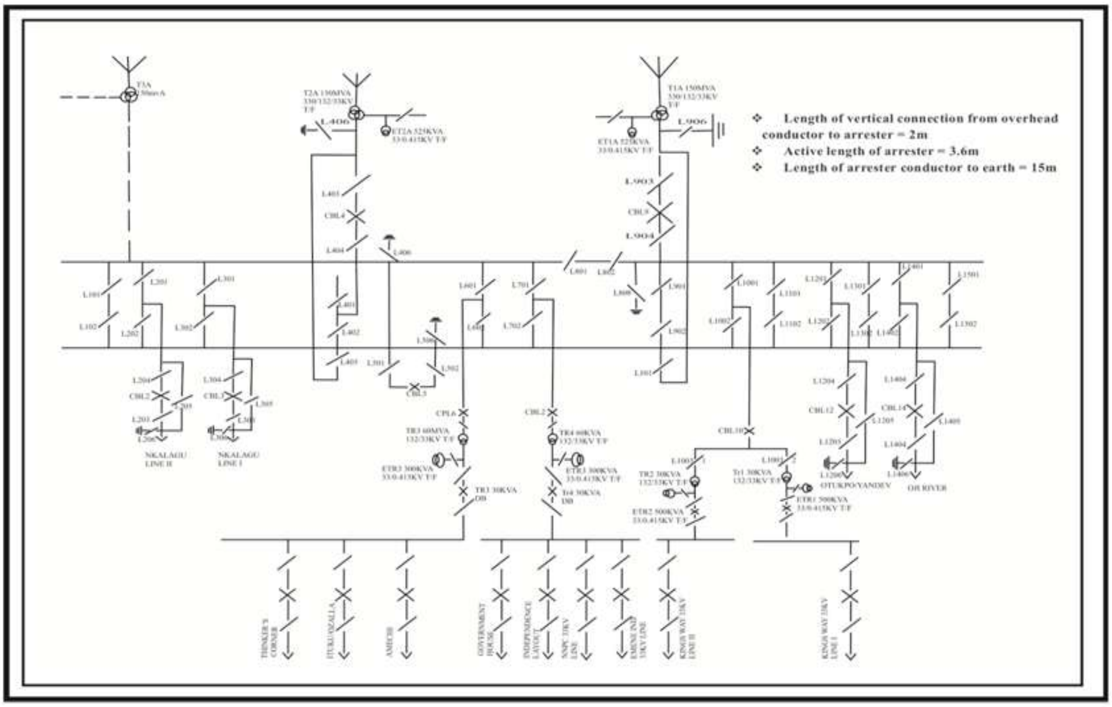


FIGURE 2.: MODEL OF THE 330KV/132KV POWER STATION AT NEW HAVEN ENUGU NIGERIA USED FOR THE INSULATION COORDINATION TESTING



- Length of vertical connection from overhead conductor to arrester = 2m
- Active length of arrester = 3.6m
- Length of arrester conductor to earth = 15m

Figure 3 NEW HAVEN 132/33 kV T/S SINGLE LINE

The results for the three scenarios, combined plot of the scenarios and waveform at the strike point are shown in Figures 4 to 8.

IV. Presentation Of Results

In the scenario A, the lightning strike occurs at 45m to the A-phase entrance to the 132/33kV segment of the system on the line of protection arrester 4. Thus, the lightning overvoltage waveform at the arrester 4(i.e. phase A arrester) is as depicted in figure 4.

The lightning strike occurs at 45m to the entrance arresters(i.e. arrester 4 on phase A, arrester 5 on phase B and arrester 6 on phase C).This is followed by a secondary strike. For this scenario, the lightning overvoltage waveform at arrester 4(i.e. phase Aarrester) is given on Figure 5.

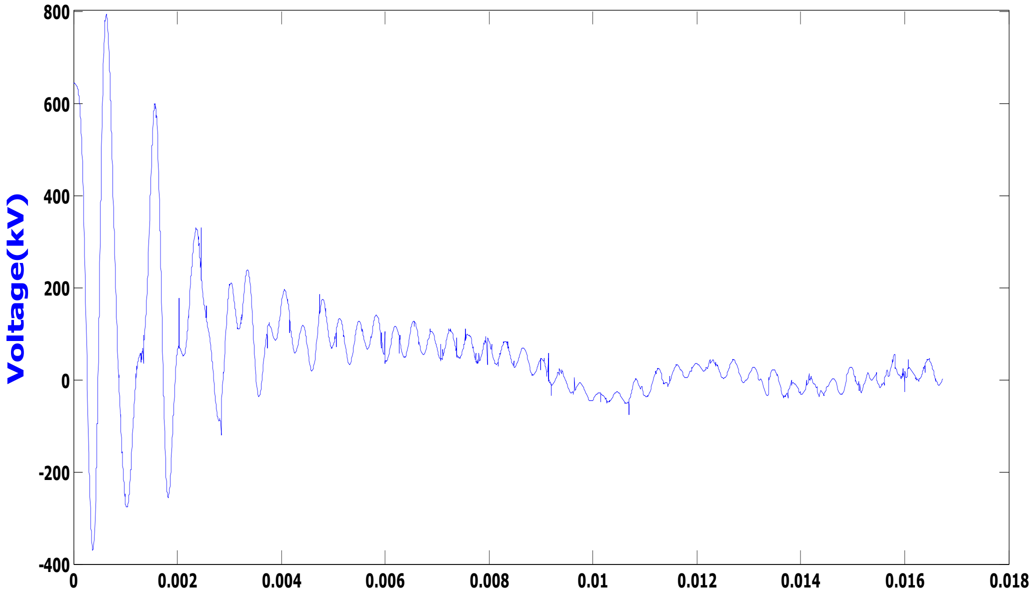


Fig. 4: RESULTANT WAVEFORM SURGE EVENT SCENARIO A

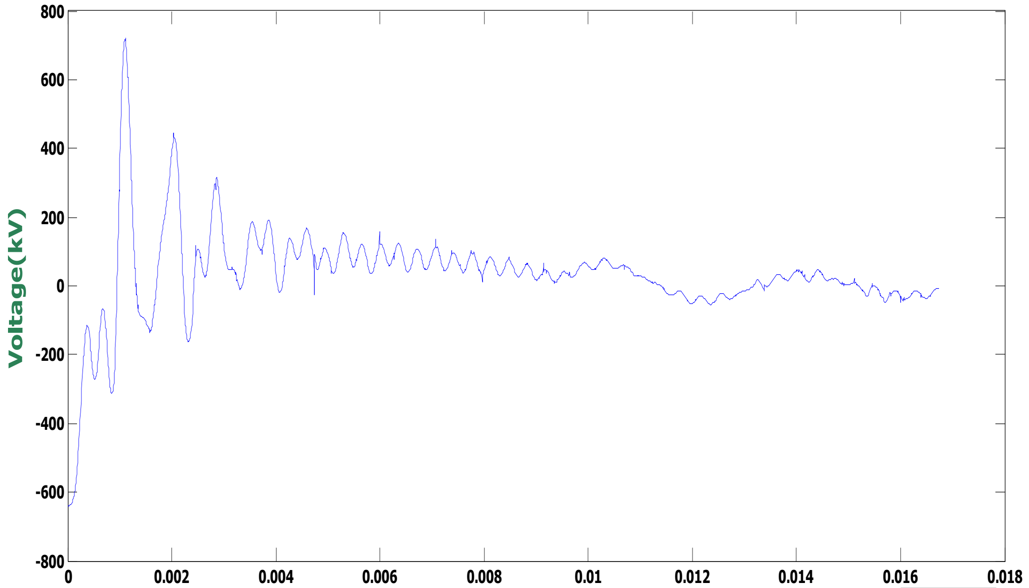


Fig. 5: RESULTANT WAVEFORM FOR SURGE EVENT SCENARIO B

In Scenario C, the lightning strike occurs at 90m to the entrance arresters, linking to the Kingsway 33kVline(i.e. arresters 4, arrester 5, and arrester 6). The lightning overvoltage waveform at arrester 4(i.e. phase A arrester) is given in figure 6.

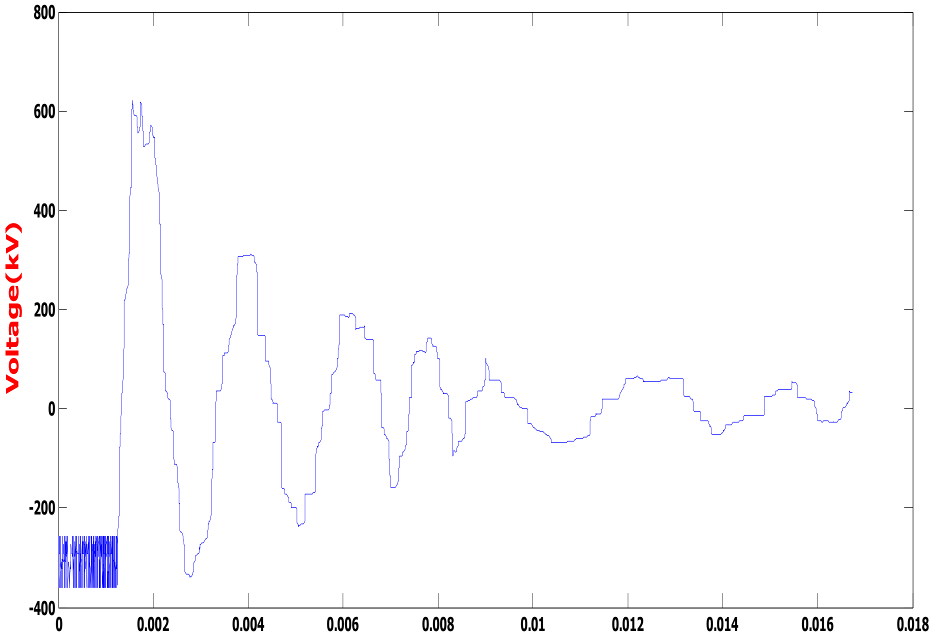


Fig. 6: RESULTANT WAVEFORM FOR SURGE EVENT SCENARIO C

A combined plot of the resultant waveforms of the three scenarios is shown in figure 7. This amplitude comparison becomes clearer in the combined plot given in Figure 7. Though the amplitude of the surge signal of Figure 4 of highest magnitude of the three, the HMM algorithm still identified that of figure 5 as having the highest maximum likelihood.

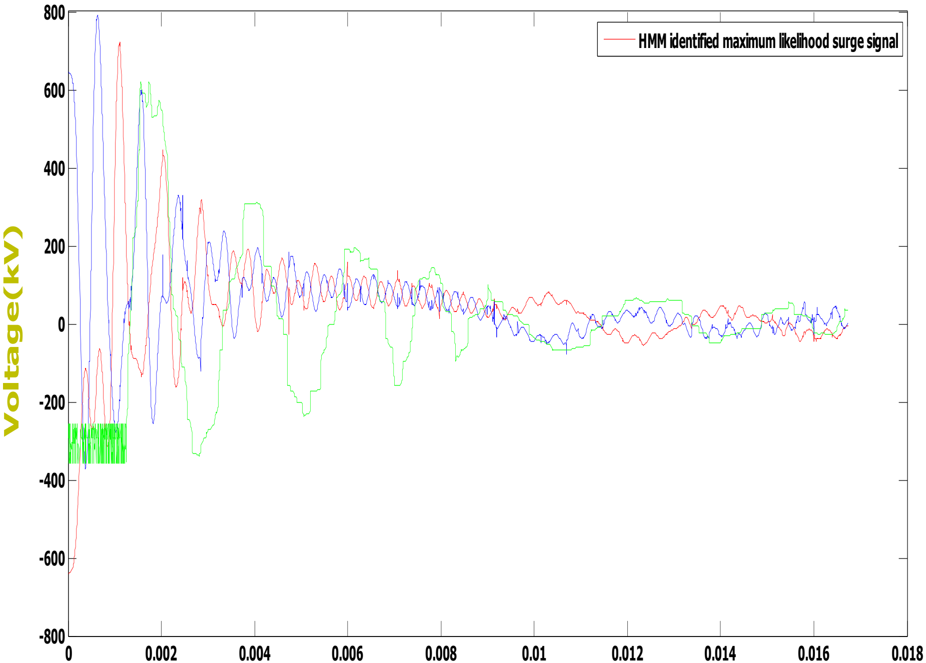


Fig. 7: RESULTANT WAVEFORM OF THE THREE SURGE EVENT SCENARIOS

The waveform at the lightning strike point is given by Figure 8. At the strike point is given(of 45m to the entrance arresters), the wave shape is that of impulse wave with an exponential curve that rises quickly to the peak and falls comparatively slowly towards zero with respect to time.

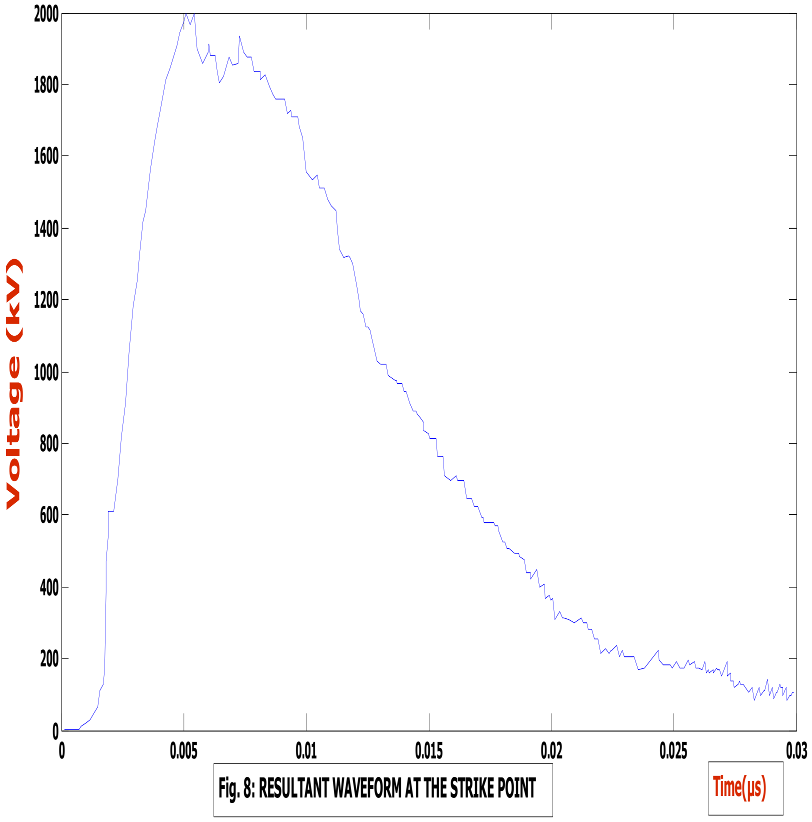


Fig. 8: RESULTANT WAVEFORM AT THE STRIKE POINT

V. Discussion Of Results

From the simulation studies, the waveform that is identified as having maximum likelihood is that of figure 5. But it should be noticed by comparing the maximum amplitude of Figure 4 and 5 that the surge wave of Figure 4 is of a higher amplitude. This amplitude comparison becomes clearer in the combined plot given in Figure 7. Though the amplitude of the surge signal of Figure 4 is of highest magnitude of the three, the HMM algorithm still identified that of figure 5 as having the highest maximum likelihood. This can be understood from the fact that HMM is based on probability distribution, rather on deterministic measurement. This means from the iterations, the signal waveform of Figure 5 has the highest probability strength than the other signals, based on the complex structure of the power system dynamics as seen by the algorithm.

From the Calculation results, the following points can be made:

1. The BIL of the transformer supplied is greater than the Maximum surge voltage.
2. The Arrester residual voltage must be below the protected equipment with a suitable margin.
3. The IEEE13131.2and the IS/IEC 60071-2recommended margin is between 15% and 25%.
4. Margin above 15% is more recommended.
5. The margin of protection = $\frac{850 - 732.26}{732.26} \times 100\% = 16.08\%$
6. The MOP is just a little above the recommended.
7. Adjusting the Arrester/Transformer distance can improve the MOP.

For instance, to achieve a protection margin of 18% at the switch yard, the maximum permissible surge at the transformer is

$$E_t = \frac{850}{1.18} = 720.34\text{KV} \qquad (9)$$

Where E_t is defined as the maximum permissible surge at the transformer as shown in equation (10)

$$E_t = E_a + \beta \frac{de}{dt} \times \frac{2L_t}{300} \qquad (10)$$

Substituting equation (9) into equation (10)

$$720.34 = 650 + 0.6 \times 3163.68 \times \frac{2l_t}{300}$$

Hence, $l_t = 5.56m$

VI. Conclusion

The lightning surge arrester 4 has to be placed 5.56m to the transformer in order to achieve a protection margin of 18%.Based on the HMM identified maximum likelihood lightning surge waves, resulting from the three lightning disturbance scenarios at the power station investigated, the arrester – transformer placement meets the minimum margin of placement. The minimum required margin of 15% is exceeded by a little value(about 1.08).Also, evaluation carried out to raise the protection margin to 18% meant the relocation of the arrester to within 5.56m of the transformer.Thus, basing the selection of coordination, lightning surge wave signal on probabilistic maximum likelihood is an optimal approach in providing the economic – technical safety trade off.

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