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SURGE TRANSFER BEHAVIOUR OF POWER TRANSFORMERS

BY

Dr. Suhail Aftab Qureshi and Humayun Pervaiz

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ABSTRACT

When switching occurs in a power system, voltage transients are produced. These transients travel along the transmission line in the form of a travelling waves and are reflected and refracted where there is a change in the impedance of the transmission line. These transients while travelling on transmission lines reaches power transformer and transfer to the secondary side. The transient voltage which appears on the secondary mainly depends on type of transient and capacitance and inductance of transformer and the equipment connected to the secondary side..

In this paper the surge transfer behaviour of the power transformer is presented as this is the main component of a power system which is subjected to voltage transients after transmission line. Transformer models for both low frequency and a high frequency are derived and modeled in EMTP (Electromagnetic Transients Program). Different types of surges are then applied to its primary side and the secondary voltage is determined with the change in transmission line length and load power factor. It is observed that for high frequency voltage transients the behaviour of transformer is capacitive while for low frequency transients it is inductive.

Keywords: transformer, surge transfer, EMTP,

INTRODUCTION

When a power frequency voltage is applied to one winding of a transformer, power frequency voltage appear at the terminals of its other windings, the amplitude of which is determined by the turn ratio between the respective windings. But this is not true for other frequencies. The transformer behaves like a filter suppressing some frequencies and passing other. The inductive element of the transformer are important at low frequency whereas the capacitive elements dominate at high frequency.

When transients are produced in a power system and travel along the transmission line, there is strict proportionality between voltage waves on the transmission line and their associated current waves. The proportionality factor is the characteristic impedance *Zo* of the line. When a waves arrives at a nodal point/discontinuity, where characteristic impedance of the line changes, some adjustment must occur if the proportionality is not to be violated. This adjustment take in the form of initiation of two new wave pairs, the reflected and transmitted waves. The reflected voltage wave and its companion current wave travels back down the line superimposed on the

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[1]Associate Professor, Department of Electrical Engineering, University of Engineering and Technology, Lahore, Pakistan

[2]Assistant Director, WAPDA, Lahore, Pakistan

incident wave, while the transmitted waves penetrate beyond the discontinuity in the forward direction. The amplitude of the reflected and transmitted waves are such that the voltage to current proportionalities are preserved for each, as demanded by the characteristic impedance of the line on which these waves are traveling.

The reflected waves travel back and forth on the line setting up in turn further reflected waves at the ends. This process continues indefinitely unless the waves are attenuated completely due to resistance of the line and corona effect.

In the study of electromagnetic transients resulting from circuit switching in power system, transformers are usually represented by their leakage impedance at power frequency This simulation may not be correct in some conditions in which relatively high frequency transients are involved, e.g. busbar switching in substation and clearing short distance faults. For the study of lightning surges, transformers are modeled by their entry capacitance [Su, Q., James, R.E. and Sutanto, D.,1990]. This model may not be valid for the surges which have a slower wave front when reaching a transformer because inductances of transformer could effect the transients as well.

Fig 1 is a simplified representation of a two winding transformer showing pertinent capacitances between the windings and from the secondary to core (which is represented by ground). This winding/core combination form a coaxial system of capacitors, with capacitances C_1 and C_2. Thus the winding and the core constitute together a crude potential divider.

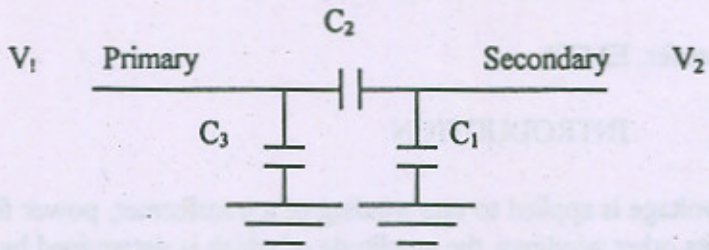


Figure 1. Capacitive coupling between primary and secondary windings of a transformer.

When a surge of voltage V_1 is applied to a series combination of capacitors, the voltage divides inversely as the capacitance. The potential of secondary winding attains a value

$$V_2 = \frac{C_1}{C_1+C_2} \times V_1$$

where V_1 is the surge voltage. C_1 and C_2 are determined by the geometry of the coil and core structure. V_2 represents a significant fraction of the surge voltage , it bears no relationship to the turn ratio of the transformer. When the primary winding is simply energized, especially if it occurs near the peak of the voltage wave, a considerable fraction of the primary voltage may appear on the secondary winding. For low frequency switching surges inductive elements are also included in the model.

At low frequencies the transformer presents inductive behavior while at higher frequencies the capacitive behavior is more dominant. For frequencies which are not very high or very low, a model of a transformer is needed which can cater for both the high frequencies and the low frequencies

CAUSES OF VOLTAGE TRANSIENTS

There are many events in power system which create steep fronted voltage transients which can cause nonuniform voltage distribution and severe dielectric stresses [Greenwood, A.,1971]. Generally these transients arise as a consequence of sudden collapse of voltage, flash over of an insulator, closing or opening of a circuit breaker which could have operated normally or due to a fault. Lightning can also be a cause of a fast transient.

MODELING OF POWER SYSTEM COMPONENTS

Source

In the present work instead of representing a sinusoidal voltage source and a circuit breaker and then performing operations on the circuit breaker, an impulse voltage source is directly connected to the primary winding . Following types of waveforms are applied at the transformer winding.

1. Step wave of 3 μsec duration
2. Double exponential wave forms of the following types.
   i) 1.2x40 μsec
   ii) 5x1000 μsec
   iii) 75x 800 μsec
   iv) 250x2500 μsec

The first two waveforms are fast transients while the remaining three are slow transients

Transformer

1. Low Frequency Model

Considering electromagnetic transients due to switching operation, transformers can be represented by Inductance (L) or inverse inductance $(L)^{-1}$ matrices according to the differential equations [Brandwajn, V., Dommel, H.W. and Dommel, I.I., 1982:]:

$$[V]=[R][I]+[L]\frac{d}{dt}[I]$$

$$\text{or } [V] = [Z][I] \qquad (1)$$

$$\text{where } [Z] = [R] + j\omega[L]$$

The matrix in Eq. (1) is symmetric. Its diagonal elements are measured by excitation (no load) tests and off-diagonal elements by short circuit test. It is also possible to represent a transformer by its admittance matrix. So Eq. (.1) can also be represented as;

$$[I] = [Y][V]$$

$$\text{and } [L]^{-1} = j\omega[Y] \qquad (2)$$

Eq. (2) is a loop equation meaning that the winding segment are not yet been connected. This is accomplished by Kron's power invariant transformation matrix [Denegeff, R.C.,1978].

$$[Ln]^{-1} = [T][L]^{-1}[T]^t$$

where $[Ln]^{-1}$ = Inverse nodal inductance matrix
and $[T]$ = Transformation matrix

2. High Frequency Model

In a transformer capacitance is also present along with inductance. This capacitance is in between the layers of the same winding , between different windings and in between windings and the ground. The capacitance between portions of the same winding is present in parallel with inductance of the same winding. The capacitances between winding and ground act in parallel with the inductance between the points where the capacitances are located and the grounded point of the winding if such an earth exists. Therefore various parallel combination of inductance and capacitance in series with various other similar combination.

For the analysis of high frequency transient transfer in transformer ,terminal capacitance of the transformer is connected across each phase and in between phases and ground. Fig.2 shows plot of typical three phase transformer capacitances. For transient analysis this capacitance is halved and is lumped at each end of the winding [EMTP rule book , 1989].

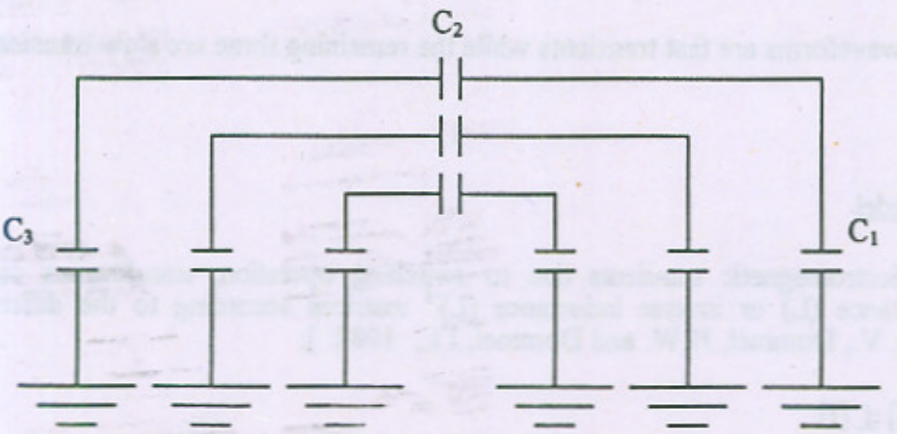


Figure.2 Capacitance model representation of a transformer

The complete transformer model for surge transfer is thus obtained by super imposing the capacitance model on the inductance model as shown in fig.3. The capacitance are simply added as extra branches connected to the transformer terminals.

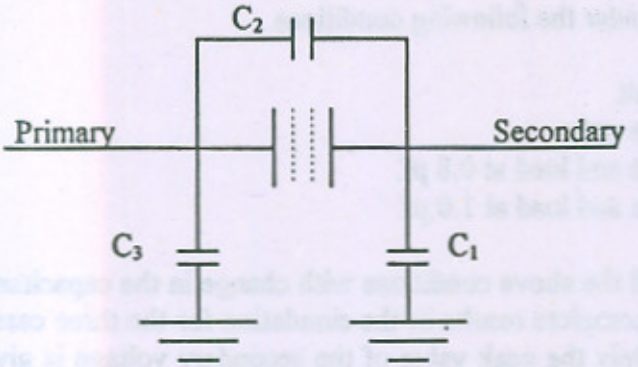


Figure.3 Complete model representation of a transformer

Transmission line

Three phase distributed parameter transmission line is simulated in this work.

Load

Load is represented as resistance (R) and inductance (L). Different values of R and L are used for 0.8 and 1.0 power factor having same MVA capacity.

The data used for different parameters of transmission line, transformer and load are given in Appendix.

NETWORK REPRESENTATION

A network shown in fig.4 is used to simulate the surge transfer characteristics of a power transformer. Different transmission line lengths, load and capacitance ratio are used to generalize the results.

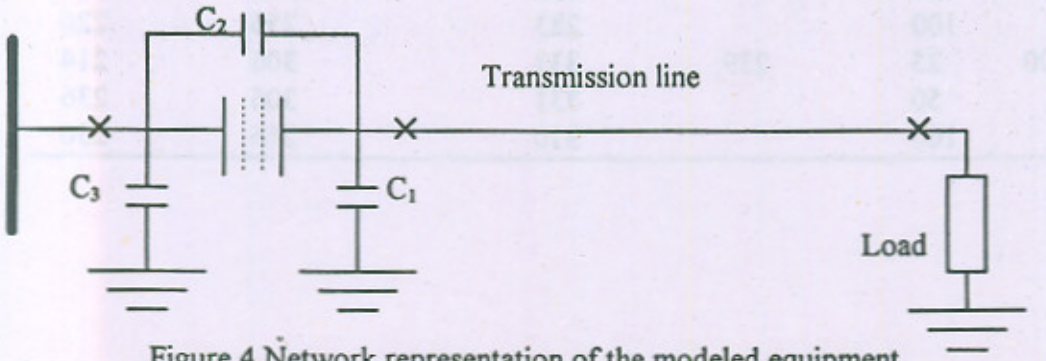


Figure.4 Network representation of the modeled equipment.

RESULTS

In order to investigate the surge transfer behavior of the transformer, detailed analysis has been made. A surge of 500 KV is applied to the primary of the transformer and the transferred surge is observed on the secondary side under the following conditions.

1. Transformer secondary open circuit
2. Transformer with transmission line only
3 Transformer with transmission line and load at 0.8 pf.
4 Transformer with transmission line and load at 1.0 pf.

Three cases are performed with all the above conditions with change in the capacitance of the transformer [Pervaiz, H.,1997]. The complete results of the simulation for the three cases are given in tables 1, 2 and 3 respectively. Only the peak value of the secondary voltage is given in these tables. The waveshape of the voltage is not considered. The observation time for the determination of secondary voltage is also different for different inputs.

Table 1
(C_1=5nF and C_2=5nF)

(KV)

Input	Length of T/L in km	Secondary open	With T/L only	T/L & Load at 0.8 pf	T/L & Load at 1.0 pf
Step input	25	249	233	233	233
	50		233	233	233
	100		233	233	233
1.2x40	25	243	201	201	201
	50		201	201	201
	100		201	201	201
5x1000	25	262	367	342	221
	50		343	316	221
	100		301	275	221
75x800	25	245	361	334	226
	50		332	305	226
	100		283	256	226
250x2500	25	239	333	306	214
	50		331	306	236
	100		310	286	236

Table 2
(C_1=4nF and C_2=6nF)

(KV)

Input	Length of T/L in km	Secondary open	With T/L only	T/L & Load at 0.8 pf	T/L & Load at 1.0 pf
Step input	25	200	186	186	186
	50		186	186	186
	100		186	186	186
1.2x40	25	197	161	161	161
	50		161	161	161
	100		161	161	161
5x1000	25	267	365	340	219
	50		341	316	219
	100		300	275	219
75x800	25	247	359	333	224
	50		339	304	224
	100		282	255	224
250x2500	25	241	333	307	214
	50		331	307	236
	100		311	287	236

Table 3
(C_1=5nF and C_2=4nF)

(KV)

Input	Length of T/L in km	Secondary open	With T/L only	T/L & Load at 0.8 pf	T/L & Load at 1.0 pf
Step input	25	277	256	256	256
	50		256	256	256
	100		256	256	256
1.2x40	25	268	218	218	218
	50		218	218	218
	100		218	218	218
5x1000	25	277	366	340	221
	50		342	316	221
	100		301	274	221
75x800	25	250	357	330	223
	50		328	301	223
	100		280	253	223
250x2500	25	241	333	306	214
	50		331	306	236
	100		310	286	236

It is observed from the results in table 1,2 & 3 that for step input and 1.2x40 μsec input, the secondary voltage for T/L only and for T/L with 0.8 pf and 1.0 pf remains the same. This is because the voltage which appears on the secondary is only the transferred voltage due to capacitance of the transformer and further there is no reflection of voltage from the far end. By increasing the observation time no change in the peak is observed as the reflected wave is of less magnitude and there is no superimposing of the reflected wave on the incident which may cause change in the secondary voltage as with the case of other slow fronted waves

Results of simulations given in tables 1, 2 and 3 also shows that short fronted surge wave is less effected by the increase in the transmission line length connected at the secondary terminal of the transformer but on the capacitance ratio. On the other hand the switching surge i.e. long fronted/tailed surge is greatly effected by the length of the line connected at the secondary of the transformer. Increase in magnitude is due to the reflection phenomenon during which the reflected wave super imposes on the incident wave.

For short line length the magnitude of the surge at the secondary of the transformer is high as compared to the longer line length. This is due to the fact that reflected wave takes less time to return in short transmission line. So as the length increases, the magnitude of the surge decreases. This is the reason why short line faults are more severe than long line faults.

From the results shown in tables 1, 2 and 3 it is also observed that the load connected at the end of the transmission line has a great impact on the magnitude of the surge occurring at the secondary of the transformer. This is due to the fact that with the improvement in the power factor the impedance of the load tends to match with that of the transmission line and much of the wave is refracted and less is reflected back. The magnitude of the surge decreases by 20% as the power factor of load approaches unity.

The results of the simulation shows that change in the capacitance ratio greatly effects the magnitude of the transferred surge at the secondary for fast transients. While transformation of slow transients are not effected with the change in capacitance ratio. This confirm that the surge wave transformation of slow fronted transients are effected mainly electromagneticaly.

CONCLUSIONS

Following conclusions are made from this research work

1- For very short duration transients the capacitive effect of transformer is more dominant.
2- For transients of moderate and long duration, inductance of the transformer also plays an important role.
3- The peak voltage at the secondary terminal reduces with increase in transmission line length.
4- The peak voltage at the secondary of the transformer also reduces with the improvement in power factor as the impedance of the load tends to match with that of transmission line.

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APPENDIX

The power system components data is presented in the appendix

Transmission line

Distributed parameter transmission line is simulated in this work. The parameters of the transmission line are as under:

	Resistance (ohms)	Inductance (mh)	Capacitance (μF)
Zero sequence impedance	0.2598	3.319	0.00786
Positive sequence impedance	0.02405	0.9239	0.0126

All these parameters are per km based. Transmission line lengths of 25, 50 and 100 km are used to see how it effects the surge transfer. Surge impedance of the line is 270.78 ohms.

Transformer

The data of the core type transformer used for the present work is given below:

Connection	Voltage (Kv)	Resistance (Ohms)
Grd-Y H.V. Winding	230.0	0.205466
Grd-Y L.V. Winding	109.8	0.074233
Delta Ter: Winding	50.0	0.082200

Positive Sequence Impedance

Winding	Z +Ve (%)	Mva Base
1 - 2	8.74	300
1 - 3	8.68	76
2 - 3	5.31	76

Zero Sequence Impedance

Winding	Zo (%)	Mva Base
1 - 2	7.34	300
1 - 3	26.26	300
2 - 3	18.55	300

No Load Exciting Current

Ie +ve 0.428% on 300 MVA

Pe +ve 135.73 KW

Transformer Capacitance

Case-1

L.V.winding to ground	(C_1)	5nF
H.V. winding to L.V.winding	(C_2)	5nF
H.V.winding to ground	(C_3)	2.5nF

Case-2

L.V.winding to ground	(C_1)	4nF
H.V. winding to L.V.winding	(C_2)	6nF
H.V.winding to ground	(C_3)	2.5nF

Case-3

L.V.winding to ground	(C_1)	5nF
H.V. winding to L.V.winding	(C_2)	4nF
H.V.winding to ground	(C_3)	2.5nF

Load

	Resistance (ohm)	Inductance (milli-henry)
0.8 pf	38.04	94.92
1.0 pf	47.52	