SYMPATHETIC INRUSH PHENOMENA IN PARALLEL AND SERIES CONNECTED TRANSFORMERS USING PSCAD

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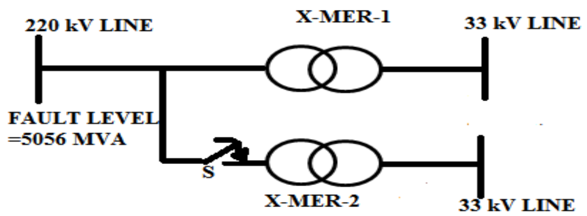
Abstract: This paper discussed sympathetic inrush and inrush phenomenon on parallel, series and parallel-series connected transformers. Sympathetic inrush current is the transient current which is drawn by already energized transformer while another transformer is energized and connected in series/parallel combination with the existing one. These currents have many adverse effects, like mal operation of transformer differential protection, insulation failures, degradation of mechanical support structure of windings and disturbed the power quality of the system[1-2]. In short circuit laboratory, magnitude of these currents can be reduced using control switching circuitry. If Short circuit and energization of transformers occurs at same moment, that moment magnitude of these currents are less compared to normal no load energization. All those results obtained from 50 MVA, 220/33 kV, three-phase transformer. Magnitude and duration of these currents depend upon many factors, like air core reactance, system fault level, point on wave switching, residual flux density, number of banked transformers, transformer design and load conditions. Simulation results obtained from PSCAD are also analyzed and discussed.
Keywords: Short circuit, Sympathetic inrush current, Controlled switching, PSCAD.

I. INTRODUCTION

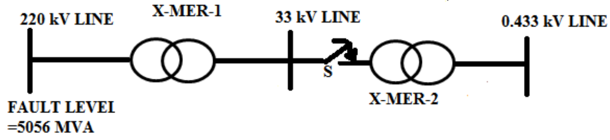
Short circuit test laboratory realized inrush and sympathetic inrush problem during energization of test object transformer which is draw the transient current. The test object (transformer-2) realized inrush current which is six to eight times of rated current and short circuit testing transformer (transformer-1) realized sympathetic inrush current which is shown in fig.1 (b). To test higher rating of transformer, a high fault level is required. This is being explored in this paper by putting another transformer in parallel to the existing transformer; Due to this short circuit fault level will be increase but there is sympathetic inrush current issue. During energization of paralleled transformers, transformer-2 realized the inrush current and transformer-1 realized sympathetic inrush current which is shown in fig.1 (a). Fig.1(c) shows the series parallel combination in which transformer-3 realized Inrush current and transformer-1 & 2 realized sympathetic inrush current.These currents can exceed the nominal current and may achieve the rated value of the short-circuit current of the power transformer. The amplitude is decaying very slowly and reaches its steady-state magnetizing current after some seconds. Transient inrush currents containing high DC-component and rich in 1st and 2nd harmonics [1], Affect the power quality and can trip protective relays. Due to these transients, huge current forces arise in the transformer windings [2] that possibly reduce the lifecycle of power transformers, The inrush current in a transformer decays, usually, within a few cycles, but the sympathetic inrush current persists in the network for a relatively longer duration. This poses an additional threat to the reliability and security ofthe power system. Finally, it may lead to an increase in the noise level of other transformers connected in the network [12].

II. SYMPATHETIC INRUSH CURRENT ANALYSIS

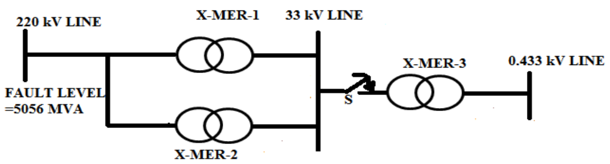
A transformer already connected to supply system can experience unexpected saturation during the inrush transient of an incoming transformer. This saturation, which is established by an asymmetrical voltage drop across the system resistance caused by the inrush current in the incoming transformer, demands offset magnetizing currents of high magnitude in the already connected transformers. As shown in Fig. 1, when transformer 2 is switched on to the network where transformer 1 is already feeding loads, the transient inrush currents not only flow through transformer 2, but also through transformers 1. This sharing of the transient inrush current is called as sympathetic inrush phenomenon.
The normal inrush current in the transformers decay, usually, within a few cycles, but the sympathetic inrush current persists in the circuit for a relatively longer duration [9-11].



(a) Parallel connection



(b) Series connection



(c) Parallel and series connection
Fig.1 Sympathetic inrush current interaction

Fig.2 shows the inrush and sympathetic inrush current in the incoming and the already energized transformer respectively. Longer duration of the sympathetic inrush current may mal-operate differential relays. It may also prolong harmonic over-voltages in the system and increase noise level in the already connected transformers. We have followed the convention of representing the inrush current in green and the sympathetic inrush current in blue in all the figures in this paper.

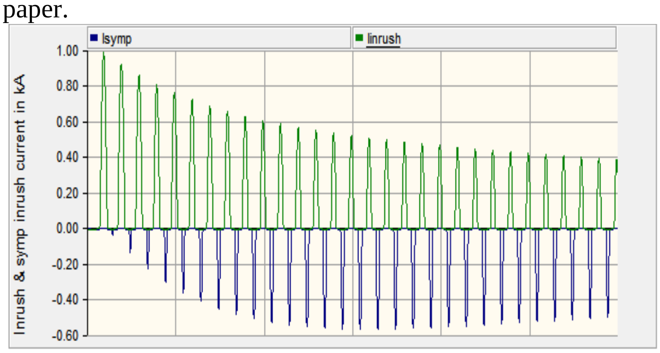


Fig.2 Sympathetic inrush and inrush current waveform

III. MATHEMATICAL CALCULATION

The simplified equation often used to calculate the peak value of the first cycle of inrush current in Amps is as follows

$$I_{pk} = \frac{\sqrt{2}U}{\sqrt{(w.L)^2 + R^2}} \left(\frac{2.B_N + B_R - B_S}{B_N}\right) \quad \text{Amps}$$

Where:
U = Applied voltage, Volts
L = Air core inductance of the transformer, Henry
R = Total DC resistance of the transformer windings, Ohms
B_R = Remnant flux density of the transformer core, Tesla
B_S = Saturation flux density of the core material, Tesla
B_N = Normal rated flux density of the transformer core, Tesla

In reality, the above equation does not give sufficient accuracy since a number of transformer connected in parallel and system parameters, which affect the magnitude of inrush current significantly, are not included in the calculation. As well, this equation does not provide information on the subsequent oscillations throughout the duration of the inrush current transient.

The calculation also incorporates the following important transformer and system parameters which can have as much as 60% impact on the magnitudes of inrush current [3-5].

The inductance of the air-core circuit adjusted for the transient nature of the inrush current phenomenon.

Impedance and short circuit capacity of the system.

Core geometry and winding configurations & connections, e.g., 1- vs. 3-phase, Y- vs. Delta windings connections, Grounded vs. non grounded Y connections, etc.

IV. COMPUTATIONAL METHODOLOGY

A 50 MVA, 220/33 kV, delta/delta, three-phase transformer is analyzed to investigate the sympathetic inrush phenomenon. The design details and name-plate data of the transformer under consideration are given in Table I. The transformer is analyzed on a per-phase basis with excitation of HV winding. Three-phase analysis is also done subsequently to compare the
inrush currents in all the three phases.

Table I Three phase parallel and series transformer data

Transformer ratings	Parallel transformer	Series transformer-1 Without POT	Series transformer-2 With POT
Input fault level	5056 MVA	610 MVA	1089 MVA
Rated MVA	50 MVA	5 MVA	9 MVA
Voltage Level	220/33 kV	33/0.433 kV	33/0.433 kV
Rated current in HV	131.21 A	87.47 A	157.45 A
Rated current in LV	874.77 A	6666.86 A	12000 A
Vector group	DD_0	DD_0	DD_0
% Impedance	7.20 %	7.15 %	7.29 %
Max. S.C. current in HV	13.26 kA	10.67 kA	19.06 kA
Max. S.C. current in LV	10.67 kA	83.67 kA	87.62 kA

All these data required for simulation. Fig. 3 shows the circuit connection diagram used in the simulation. It consists of two identical transformers, which are connected in parallel using PSCAD. The system resistances depend upon input fault level which is inversely proportional to each other. In this simulation first breaker closes after 0.100 s and second breaker close after 3.110 s. So at 0.100 s first transformer realize inrush current and at 3.110 s second transformer realize inrush current and first transformer realize sympathetic inrush current. Breaker 3 and 4 closed at 10.110 s but simulation run only for 8 s, so circuit behaves as open circuit.

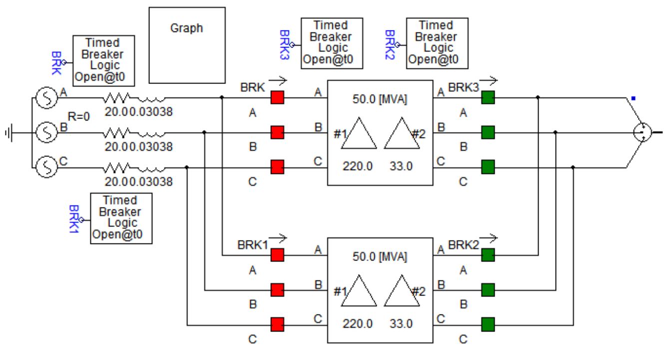


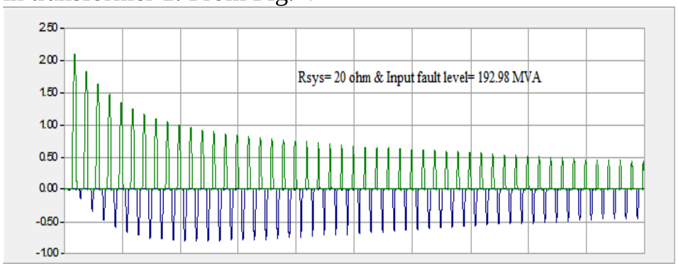
Fig.3 Connection diagram of parallel transformer in PSCAD

V. SIMULATION RESULT AND DISCUSSION

A. Parallel Connected Transformers

Parallel configuration of two transformers is shown in Fig. 3. The circuit breaker (BRK1) is closed after 3.110 second to allow initial circuit transient currents to reach their respective steady state values. For the configuration of the parallel-connected transformers, the influence of the factors such as such as air core reactance, system fault level, point on wave switching, residual flux density, number of banked transformers, transformer design and rating and load conditions, is investigated. We have followed the convention of representing X-axis represent time in second and Y-axis represent inrush and sympathetic inrush current in kA for all waveform.

Effect of input fault leval: Input fault level is inversely proportional to system resistance. Inrush current in transformer2 and sympathetic inrush current in transformer 1 are shown in Fig. 4(a), Fig. 4(b) and Fig. 4(c) for system resistances of 20 Ω, 10 Ω and 0.763 Ω respectively. Rsys reduces the magnitudes of the initial peaks of the inrush current in T2 considerably. The sympathetic inrush current experienced by the already energized transformer 1 is due to the coupling between the two transformers on account of the asymmetrical voltage drop in the system resistance Rsys of the transmission line feeding them. Hence, the higher the Rsys, the higher is the sympathetic inrush [11] as evident from the figure. However, the magnitude of Rsys has very little effect on the duration of the sympathetic inrush current in transformer 1. From Fig. 4



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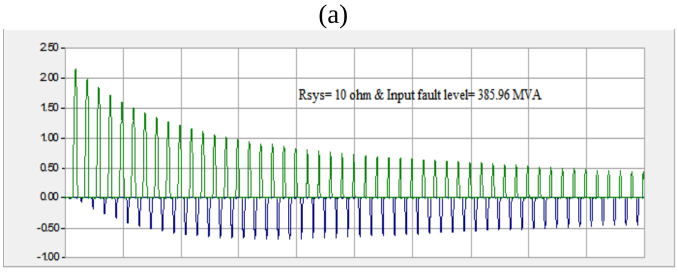

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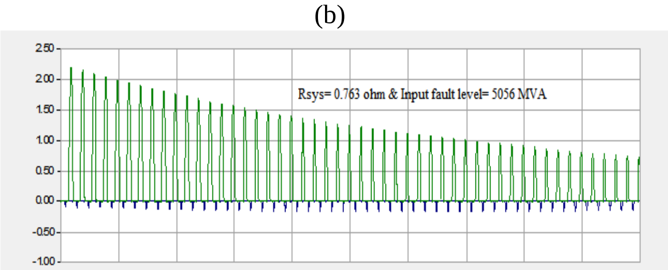

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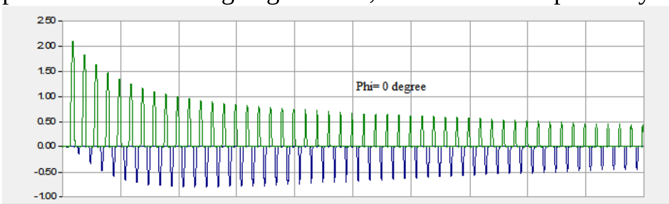
Fig.4. Effect of input fault level on sympathetic inrush current
Phenomena

Effect of point on wave switching: Fig. 5 shows the effect of point on wave switching on the magnitude of the sympathetic inrush current. Similar to the single transformer case, the magnitude of the sympathetic inrush current reduces with an increase in the switching-on angle up to 90°, and then increases in the negative direction up to 180°. The magnitudes of the inrush currents are minimum when the switching-on angle is 90°(because the inductive reactance of the transformer is much larger than the resistance). Figs. 5(a), 5(b) and 5(c) show the sympathetic inrush current patterns for switching angles of 0°, 90° and 180°respectively.



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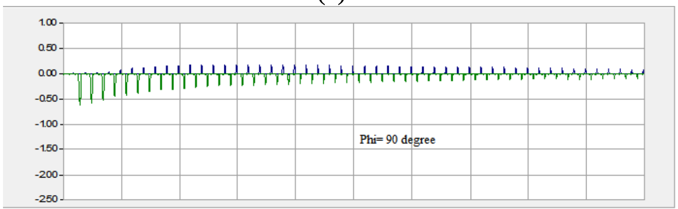

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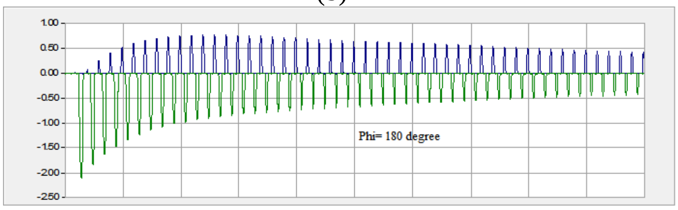

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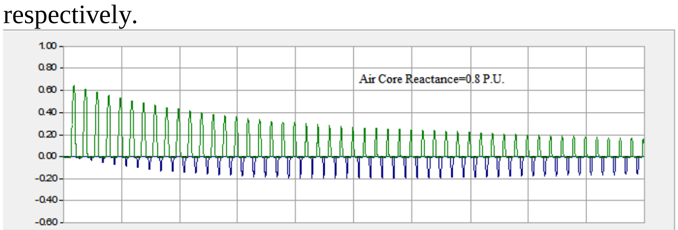
Fig. 5. Effect of point on wave switching on sympathetic inrush current phenomena

Effect of air core reactance: Similar to the single transformer case, air core reactance of the both transformer plays a key role in the sympathetic inrush and inrush phenomenon. Fig. 6 shows the inrush current in transformer 2 and sympathetic inrush current in transformer 1 at same air core reactance. It can be seen that the magnitudes of these currents largely depend on the P.U. value of air core reactance. Figs. 6(a), 6(b) and 6(c) show the sympathetic inrush current patterns for air core reactance of 0.8 P.U., 0.2 P.U. and -0.8 P.U. respectively.



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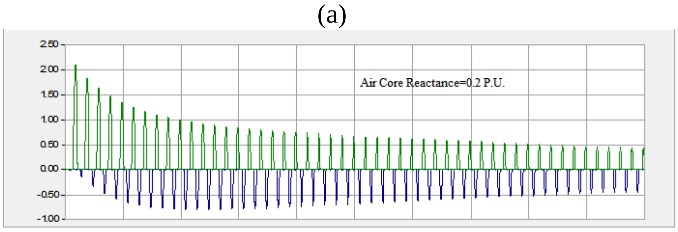

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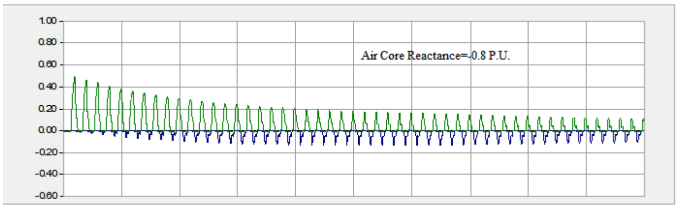

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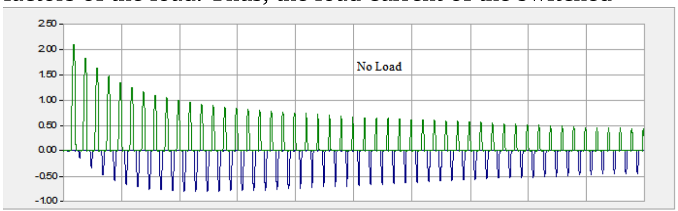
Fig.6. Effect of air core reactance on sympathetic inrush phenomena

Effect of load and power factor: When the transformer is switched on to a heavy load with power factor close to unity, the peak values of both inrush and sympathetic inrush currents are slightly smaller as compared to the no load case (see Fig. 7). The peak of inrush current in transformer 2 as well as the sympathetic inrush current in transformer 1 slightly increase with reduction in power factor as evident from Fig. 8, which shows these currents for different power factors of the load. Thus, the load current of the switched



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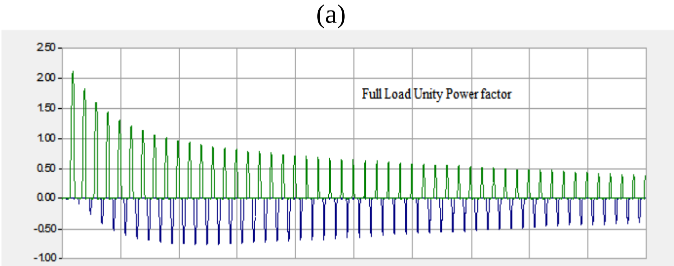

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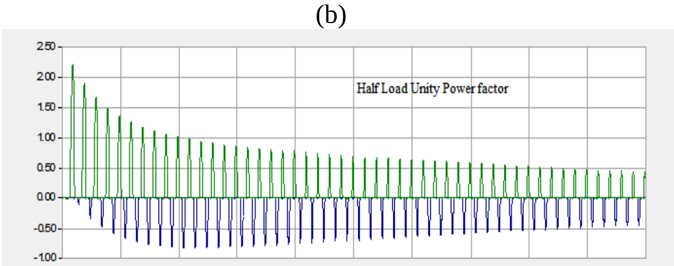

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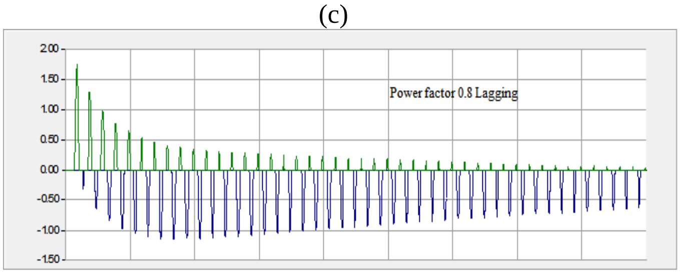


(d)

Fig.8. Effect of load and power factor on sympathetic inrush phenomena

Series Connected Transformers

In the case of transformers connected in series, the primary HV winding of the first transformer (220/33 kV, 50 MVA) is connected to supply, and its secondary winding feeds the HV winding of the transformer (33/0.433 kV, 5 MVA) being energized. The nameplate details of both the transformers are same as in Table I. Fig. 9 shows T1, the already connected transformer, and T2, the transformer that is being energized by closing the circuit breaker (BRK1).Fig.10 shows inrush current due to energization of transformer T1 and sympathetic inrush current due to energization of transformer T2 by closing BRK1.

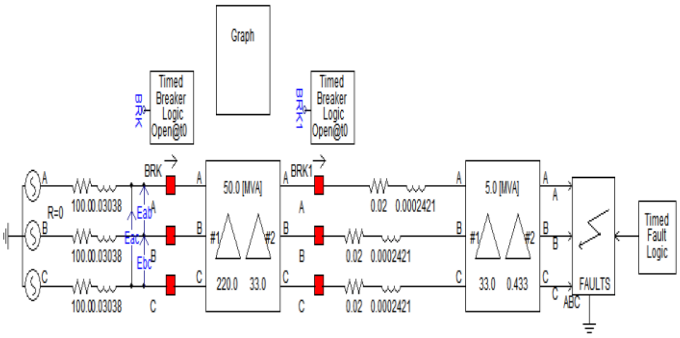


Fig.9. Connection diagram of series connected transformer in PSCAD

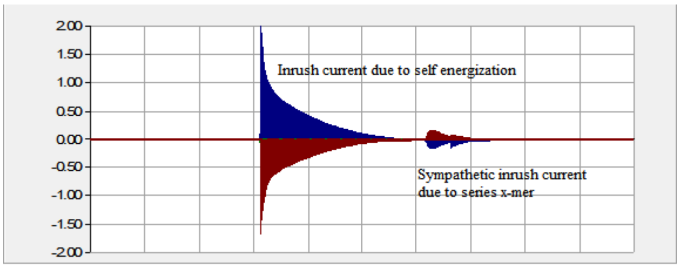


Fig.10. Sympathetic inrush phenomenon in series connected transformer

Parallel Series Connected Transformers

In the case of transformers connected in parallel series, the primary HV winding of the first transformer (220/33 kV, 50 MVA) is connected to supply through circuit breaker (BRK) and second transformer also connected to supply system through circuit breaker (BRK1),its connected in parallel with first transformer using BRK2 and BRK3. Both transformer secondary winding feeds the HV winding of the third transformer (33/0.433 kV, 9 MVA) being energized through circuit breaker (BRK4). The nameplate details of all the transformers are shown in Table I. Fig. 11 shows T1, the already connected transformer which is energized through BRK at 0.100 second and T2, the parallel transformer that is being energized by closing the circuit breaker (BRK1) at 3.110 second and T3, the series connected transformer that is being energized by closing the circuit breaker (BRK4) at 6.110 second and short circuit occurs at 8.110 second.Fig.12 shows inrush current due to energization of transformer T1 and sympathetic inrush current due to energization of transformer T2 by closing BRK1 and sympathetic inrush current due to energization of transformer T3 by closing BRK4

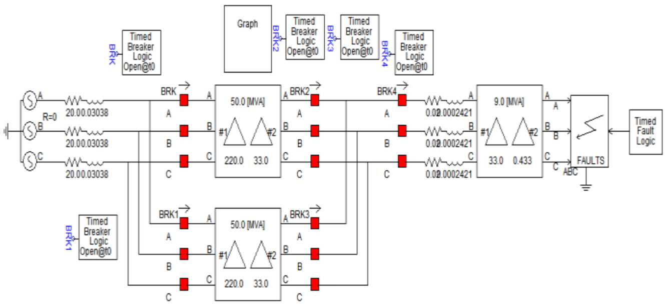


Fig.11. Connection diagram of parallel series connected transformer in PSCAD

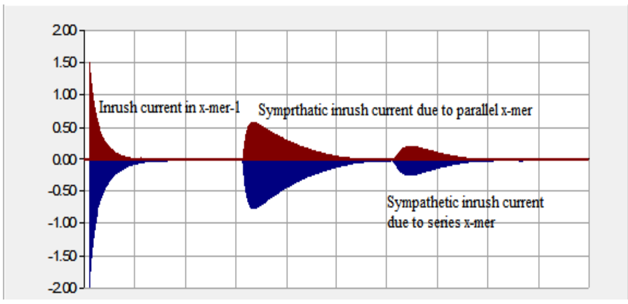
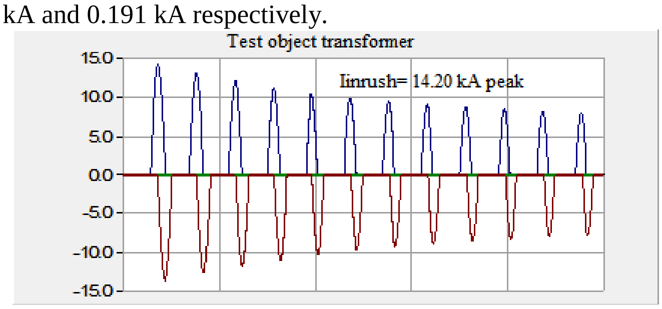


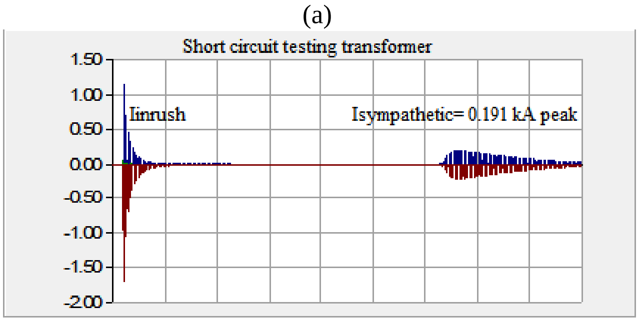
Fig.12. Sympathetic inrush phenomenon in parallel series connected transformer

Reduction of inrush and sympathetic inrush current in short circuit laboratory using control switching circuit

Fig 9 shows the short circuit test laboratory there are test object, s.c. testing transformer and master circuit breaker available. If Short circuit and energization of test object transformer occurs at different moment that moment inrush current is higher and its behave like a normal no load energization. Circuit breaker (BRK1) close at 3.110 s and short circuit occurs at 6.110 s for 0.5 s. In this case two control switches are required, results are shown in Fig 13(a) and (b) where inrush and sympathetic inrush current 14.20 kA and 0.191 kA respectively.



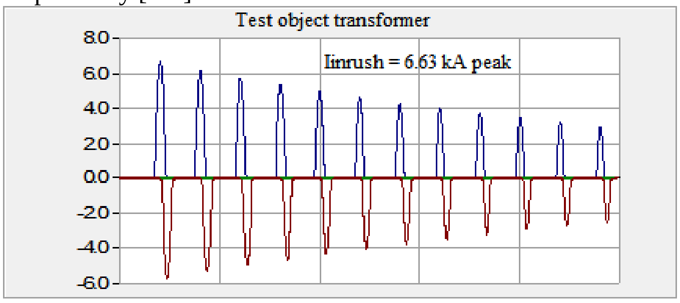
(a)



(b)

Fig.13. Inrush and sympathetic inrush current when energization and short circuit occurs at different moment

If Short circuit and energization of test object transformer occurs at same moment that moment inrush current is lower. Circuit breaker (BRK1) initially opens and close at 3.110 s and again open at 3.610 s and short circuit occurs at 3.110 s for 0.5 s. In this case practically only one control switch is required, results are shown in Fig 14(a) and (b) where inrush and sympathetic inrush current 6.63 kA and 0.002 kA respectively [6-8].



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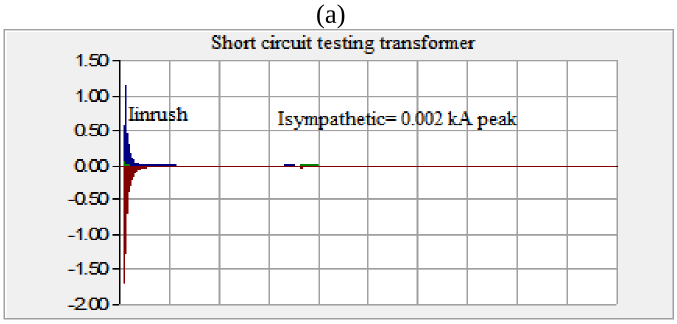

(b)

Fig.14. Inrush and sympathetic inrush current when energization and short circuit occurs at same moment

VI. CONCLUSION

It is observed that the sympathetic inrush current persists in the network for a much longer duration than the inrush current for the singly connected transformer. A number of factors affect the magnitude and duration of the sympathetic inrush and inrush current, such as air core reactance, system fault level, point on wave switching, residual flux density, number of banked transformers, transformer design and rating and load conditions are discussed in detail. It is observed that even though an increase in the system resistance increases the magnitude of the sympathetic inrush current appreciably, there is little effect on its duration. The change in switching on angle, and the magnitude and direction of the air core reactance can cause significant variations in the phenomenon of sympathetic inrush and inrush currents. Moreover, the magnitude and power factor of the load currents have only a very small effect on the magnitude as well as duration of the sympathetic inrush currents.To test the higher rating of transformer high inrush current and sympathetic inrush currents are induced in short circuit laboratory. These currents produced adverse impact on short circuit lab. To reduce these currents impact using control switching circuitry. There is only one solution which is energization of transformer and short circuit occurs at same moments. It's required only one master circuit breaker.

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