

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 6, Issue 10, October 2017

Comparative Analysis of Mitigation Techniques for Inrush Current of Transformer

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ABSTRACT:Power transformers are key element for transfer electric energy at various stages in power system. Hence stability and security of power transform is very important task in power system. During energization, due to saturation of core high magnitude of transformer inrush currents generated which may climb to ten times of rated current, thus transient inrush current which is capable to produced serious power quality problem as well as mal-operation of protection system. Hence controlling and reduction methods in order to control transient current are essentially important to the engineers in power industry. The paper discussed various methods to mitigate inrush current for three phase transformer. The investigation result show that proposed methods reduces the transient inrush current significantly.

KEYWORDS:Inrush Current, MATLAB/Simulink, Power Transformer, Sequential Switching, Neutral Resistor, Capacitor and Pre-Insertion Resistor.

I. INTRODUCTION

Due to rapid industrial expansion the demand of electric power has rapidly increased. The power is no longer a commodity but service. Hence, power quality issues related with electric power are of major concern. Transformers are significant part of the power system. The switching effects of the transformer when switched from de-energized state to energized state results into transient current through the windings of transformer popularly known as inrush current which value about 8 to 10 times as that of the normal current. The nature of inrush current is such that it slowly decreases and the subsequently attains a value which is equal to the normal rated value. It is asymmetrical and unbalanced in nature in all the phases which puts huge stress on the system network and the transformer.

This current produces various undesirable and unwanted effects such as

- 1) Hampering the operation of differential protection of transformer
- 2) Damage to the insulation,
- 3) Harm to the mechanical support structure,
- 4) Windings and serious power quality issues.

Inrush current is caused due to saturation of flux in core, due to the non-linearity of core, saturation of current, over excitation, residual magnetization and switching instant. Thus unsymmetrical and unbalance nature mainly responsible for introducing the harmonics results into harmonic, the resultant harmonics affect the performance of transformer and lead to increase in losses. The magnitude of inrush current variation is affected by magnitude of voltage, switching instant of applied voltage wave, residual flux in the core of power transformer which is generally twice of the normal flux and primary source of the transformer which is lead to the secondary of winding and size of transformer.

There are various effects of Inrush current such as emerging of hyper-electromechanical forces between windings and their dependent components. In addition to that there is unequal distribution of voltage between different parts of windings and their loops. One of the most important effects of inrush current is appearance of over current in winding.

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Due to inrush current in primary winding there can be failure of primary circuit component such as switches. Some other effects of high inrush current include unwanted circuit breaker interruption or disturbance in fuse and motor tripping. Due to inrush current stress imparted in winding of transformer which reduces the life of transformer. [2] A large amount of inrush current is capable of causing voltage sag as a result of which producing disturbance on both customers and utility side. These disturbances cause mal-functioning of sensitive electronic equipment. Disturbances in sensitive equipment can also take place due to the voltage or current magnification occurring due to resonance phenomenon resulting from inrush current. The presence of dc component in inrush current can lead to oscillatory motor torque which causes unwanted vibrations and noise. It will also enhance iron losses which notably reduced transformer efficiency. Considerably high transient inrush current in transformer primary winding which is different than secondary current of transformer. Finally results in mal-operation of relay of current transformer. [2] To overcome these effects of inrush current there are several different mitigation techniques.

This paper briefly studies different mitigation techniques for the inrush current and compares the effectiveness of some of these techniques such as sequential switching method, pre-insertion resistor method and capacitor and pre-insertion method are investigated with the help of MATLAB/Simulink. Various methods for mitigation of inrush current are simulated to find the method with best results. Section II gives out a brief glance about various causes of inrush current and its mitigation techniques. Section III deals with the system models of the techniques simulated with the help of MATLAB/Simulink and lists out the values of parameters and the corresponding values of inrush current. Section IV carries out the discussion based on the simulation results. In the end this paper on basis of results and discussion proposes the most suitable method for the suppression of inrush current.

II. MITIGATION TECHNIQUES

Various mitigation techniques have also emerged to suppress the phenomenon of inrush current such as:

1. Virtual air gap method
2. Series compensation method
3. Optical switching method
4. Point on wave switching method
5. Asymmetrical winding
6. Pre-fluxing method
7. Grounding resistance method
8. Superconductor method
9. Pre-insertions resistor method
10. Pre-insertions resistor with capacitor method
11. Sequential phase energization method.
12. Sequential switching method.

These methods are capable of suppressing the inrush current to 1 to 2 times that of normal value. There are certain challenges associated with implementation of these techniques such as the cost of employing the techniques, the complexity of control and the effectiveness of the technique.

Virtual air gap technique modifies the reluctance of magnetic circuit using auxiliary winding called air gap windings (AGW) which limits the flux & hence current will be limited but it is difficult to make appropriate air gap in core and due to the virtual air gap various mechanical problems occur. [1-4-18] The thickness of the virtual air gap is sized with help of DC source which makes the reluctance of the magnetic circuit controllable. This transient current becomes independent of the residual flux with the use of a virtual air gap inside the ferromagnetic circuit. In this method care is taken that the air gap winding (AGW) is adapted to the main circuit. [1-4-18]

Controlled point-on-wave-switching method involves with the basic concept that voltage and current have a 90° phase shift between them. Closing the line at the peak value of voltage by point-on-wave will reduce the generated amount of transient flux which in turn will reduce the inrush current in a transformer. The point on wave switching method which reduces the inrush current by switching with all winding and core configuration of power transformer & also it measures inrush current at different voltage angle. Hence in large transformer it is difficult to control residual flux in the core hence it uses in low core transformer. This method carries out integration of voltage to find out the residual

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flux. Voltage of the secondary winding is measured before the primary circuit of the transformer is opened. [1-22]
Pre-fluxing technique involves setting of the residual flux to a known polarity which is done by pre-fluxing device just before the transformer is de-energized. The method assumes that after the operation of the pre-fluxing device it will have a maximum and minimum limit of residual flux irrespective of the design. Thus instant of transformer energization calculated using this method is not accurate and optimum. This is also the reason why this method is incapable of totally suppressing the inrush current but only limiting it to a lower value [1-5]. The pre-fluxing device design itself depends on the transformer inductance which itself has a non-linear behavior which makes its design and determination very complex. [1-5]

In sequential phase energization method the neutral resistance is connected to the neutral point of the transformer. Due the energization of each phase in sequence the resistor is behave as series inserted resistor which reduce the inrush current considerably. But it is complicated than Pre-insertion resistor technique because the resistance connected between generator and transformer not to the neutral point of transformer. Hence here we use Pre insertion resistance method.[1]

Pre-insertion resistor with Capacitor method the magnitude of residual flux in the transformer is the main parameters to change magnitude of inrush current. When circuit breakers are opened transformer is isolated from network, residual flux remains in transformer and when transformer is energized inrush current will be increased. In order to reduce above affect, capacitors are inserted in primary side of transformer which reduces residual flux then inrush current is also reducing. [5]

Sequential Switching method in this method. In this method transformer each phase is energized at peak value of supply voltage of each phase. An instant of Peak value of supply voltage for each phase is different. [1-17-23]

III. SYSTEM DEVELOPMENT

In this proposed case the MATLAB model includes three phase transformer has star-star connection with neutral grounding & rating of 350MVA 500/230kV step down transformer which is under no load condition. The primary current with no load of secondary side rise to several times the rated current of the transformer. Ignoring the winding's resistance value, the relationship between the voltage and flux is describe following [13]

$$V_m \sin \omega t = N_1 \frac{d\phi(p)}{dt}$$

Where N_1 = Number of turns in primary winding

$\phi_{(p)}$ = Flux in primary winding

Flux in primary winding can be obtained as

$$\phi_{(p)} = \frac{V_m}{N_1 \omega} \cos \omega t + c$$

Now for the instant when $t=0$

$$\phi_m = \frac{V_m}{N_1 \omega}$$

$$\phi(p) = -\phi_m \cos \omega t + \phi_r + \phi_m$$

ϕ_r = Residual flux in the iron core

Now the inrush current is given as

$$I_{in} = \frac{1}{L_{in}} \int V_m \sin \omega t dt$$

Where

I_{in} = Inrush current in primary winding

L_{in} = Inductance of primary winding

V_m = Voltage from source to the primary of transformer

At the time of transient, inrush the transformer get saturated due to inrush current phenomenon. Here inrush current increases rapidly due to decrement in inductance of winding.

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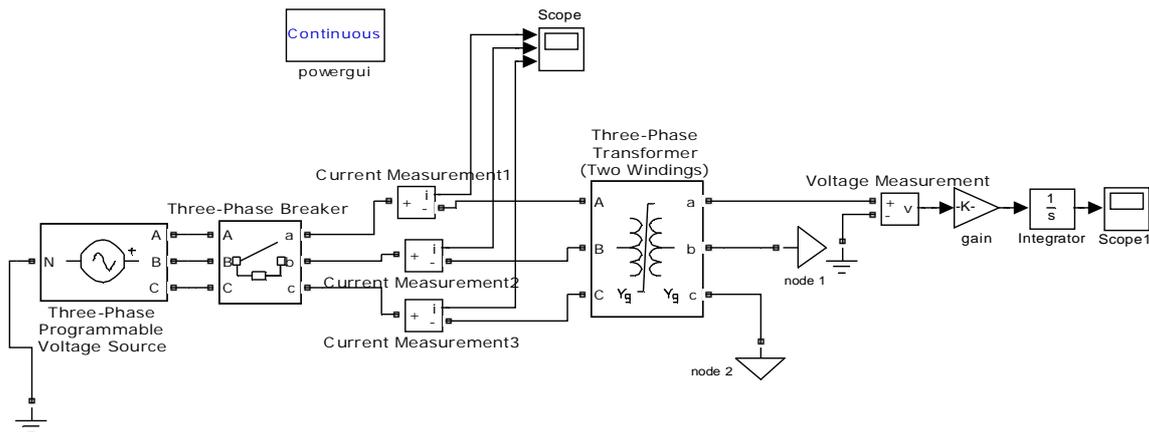


Fig. 1: Inrush Current Model without mitigation technique

Table 1 give maximum value of inrush current the result are obtained by simulating inrush current model without mitigation.

Table1: Inrush current for without mitigation model

Inrush current in phases	Peak value
Phase R	1256
Phase Y	-525.00
Phase B	-432.40

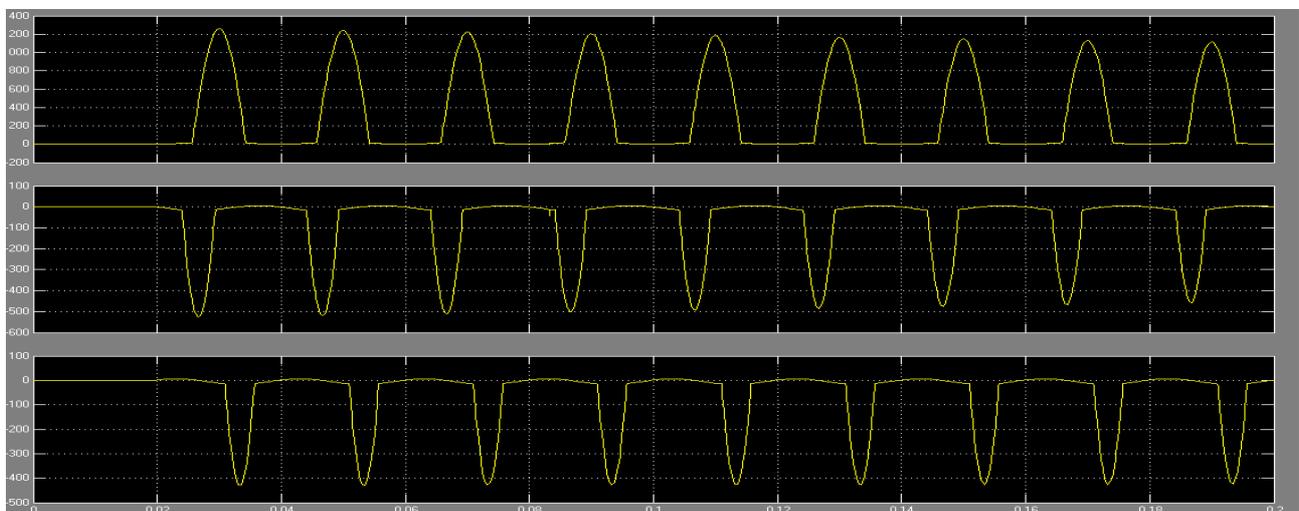


Fig 2: Inrush current without mitigation

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1. Mitigation of Inrush current by using Pre-insertion Resistance technique

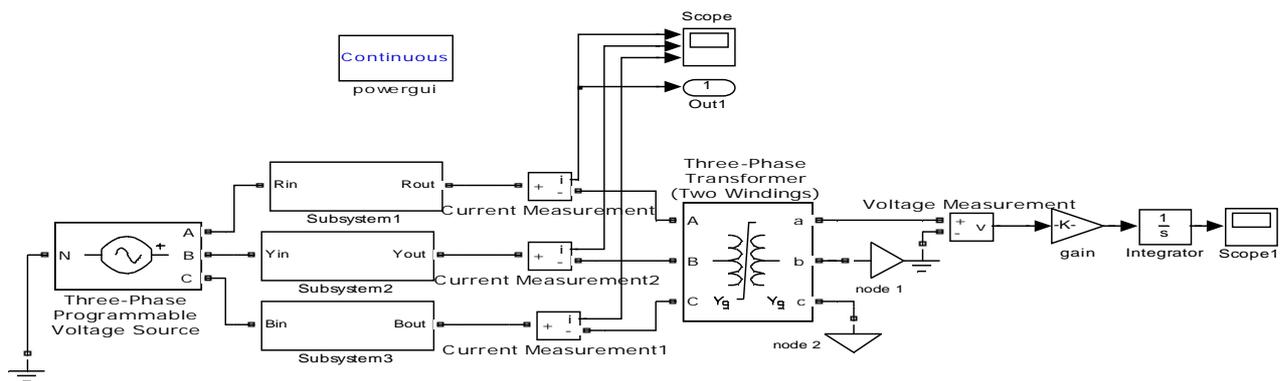


Fig 3: Model with Pre-insertion resistor method

The peak value of inrush current can be decrease by inserting the resistance between the generator and transformer. In this model initially circuit breaker 2 is closed. At the time of energisation of transformer winding the circuit breaker 1 is closed result in a resistance is inserted in series with the transformer which reduces the inrush current considerably. Table 2 shows tabulated value of inrush current for different value resistance from 0 to 400Ω. The graphical representation as shown in fig4 [23]

Table2: Inrush current for different value of resistance.

Value of resistor Ω	Phase R	Phase Y	Phase B
0	1256.70	-525.00	-432.40
25	1133.60	-445.00	-414.00
50	1050.00	-423.40	-358.00
75	984.00	-406.42	-316.40
100	922.80	-389.30	-282.40
120	880.00	-375.60	-256.40
140	841.00	-367.64	-234.00
160	805.00	-355.00	-218.00
180	772.70	-345.00	-200.00
200	743.00	-336.22	-184.00
220	714.71	-327.06	-170.00
240	688.36	-317.40	-158.34
260	664.84	-309.04	-147.50
280	642.68	-302.00	-138.00
300	622.00	-295.00	-129.00
320	602.00	-288.20	-120.00
340	584.00	-281.50	-111.50
360	567.00	-275.20	-106.50
380	550.34	-269.00	-98.00
400	535.34	-264.00	-92.50

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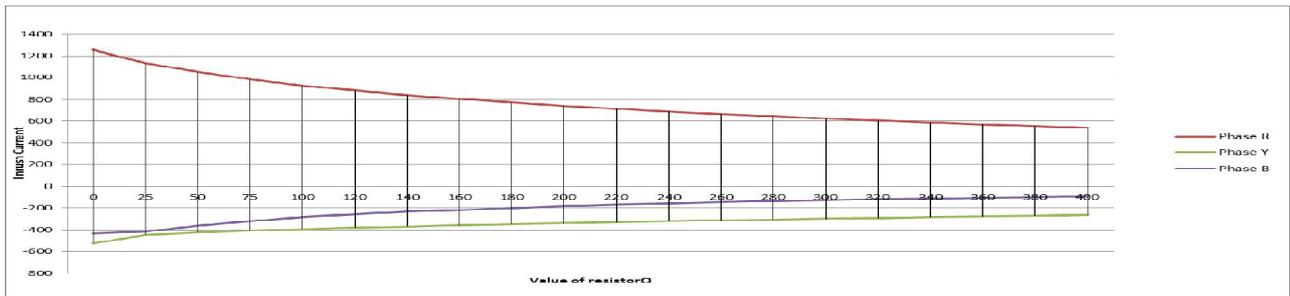


Fig 4: Graphical representation of inrush current.

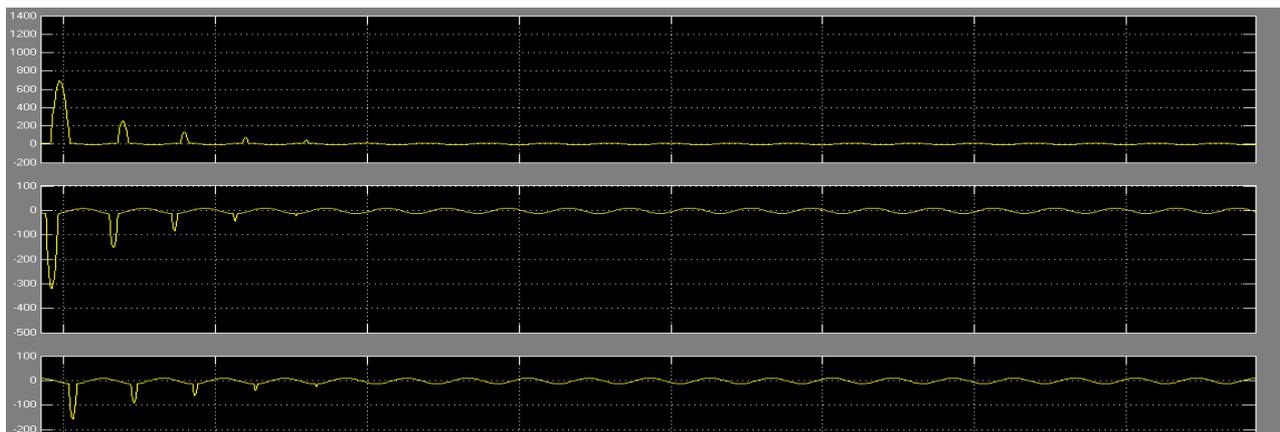


Fig 5: Results of Pre-insertion Resistor Technique

The inrush current is reducing between the values of resistor 200 to 250 rapidly and mitigate at optimal value which is mention in table 3.

Table 3: Inrush current for R = 238Ω

Optimal Value of resistance Ω	Inrush current (Amp)		
	R-phase	Y-phase	B-phase
238	691.00	-319.80	-158.00

2. Mitigation of Inrush current by using Pre-insertion Resistance with Capacitor

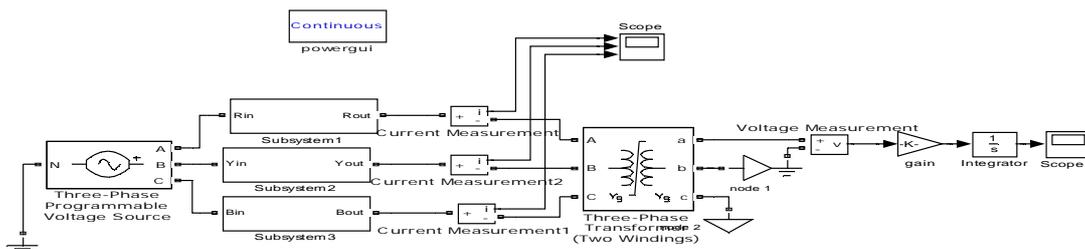


Fig 6: Model with Pre-insertion Resistor with capacitor Technique.

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The presence of residual flux in the transformer is mainly responsible for saturation of transformer core winding result in inrush current phenomenon. In order to reduce the effect capacitor is inserted in series with resistance. [5]

Table 4: For resistance R = 50 Ω

Capacitor μF	Phase R	Phase Y	Phase B
10	766	-37.64	-1136.76
20	576	-13	-620.00
25	160	-9	-675.00
30	13	-8.5	-728
40	10	13.45	-810

Table 5: For resistance R = 100 Ω

Capacitor μF	Phase R	Phase Y	Phase B
10	650	-13.282	-460
20	09	-6	-512.62
30	09	-6	-512.62
40	-150	134.5	-600
50	-237.5	331.22	-660

Table 6: For resistance R = 150 Ω

Capacitor μF	Phase R	Phase Y	Phase B
10	122	-7	-332.6
20	08	574	-280
25	-1	403.2	-200
30	-430	650	-300
40	-120	840	-360

Table 7: For resistance R = 200 Ω

Capacitor μF	Phase R	Phase Y	Phase B
10	11.3	315	-167
20	04	333	-13.5
30	-32	483	-13
40	-12	900	-13.2
50	-583	1150	-30

Table 8: Optimal values of Capacitor and resistor

Phase	R Ω	Capacitor μF	Peak value of current
R	100	20	9
Y	100	20	-6
B	200	20	-13.5

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In the pre-insertion resistor with capacitor method get the optimal values of capacitor and resistor which is mentioned in table no. 8. At these values the mitigation of inrush current is shown in fig 6.

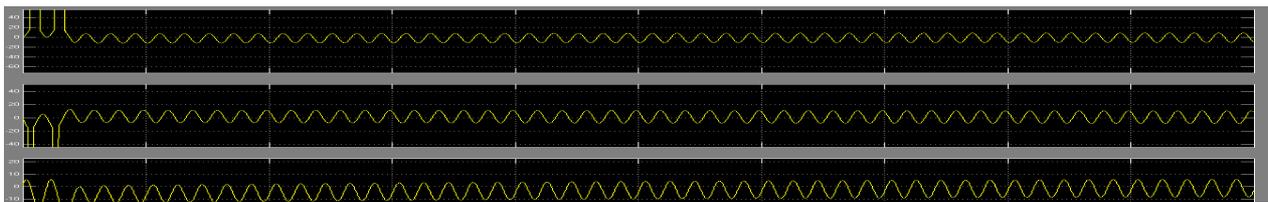


Fig 7: Current in phases R, Y and B with Pre-insertion resistor with capacitor technique

3. Mitigation of Inrush current by using Sequential Switching technique

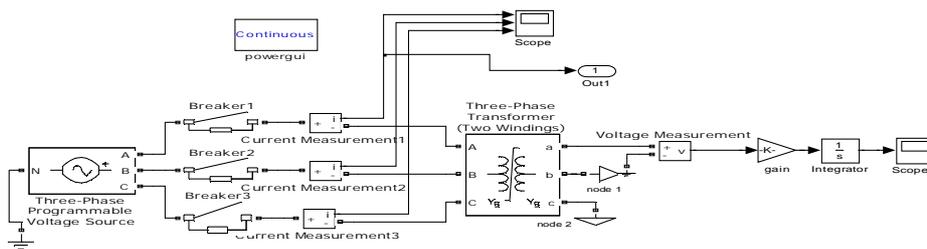


Fig8: Model with Sequential Switching Technique

In sequential switching method each phase of transformer is energized at value of supply voltage of each phase. An instant value of supply voltage for each phase is different. The optimal value of switching for R-phase [0.02576, 0.0547] for Y-phase [0.024, 0.069] for B-phase [0.0309, 0.0957]. At these instant inrush current of each phase is not only reduces but also get mitigate. The results are given in fig.9. [17]

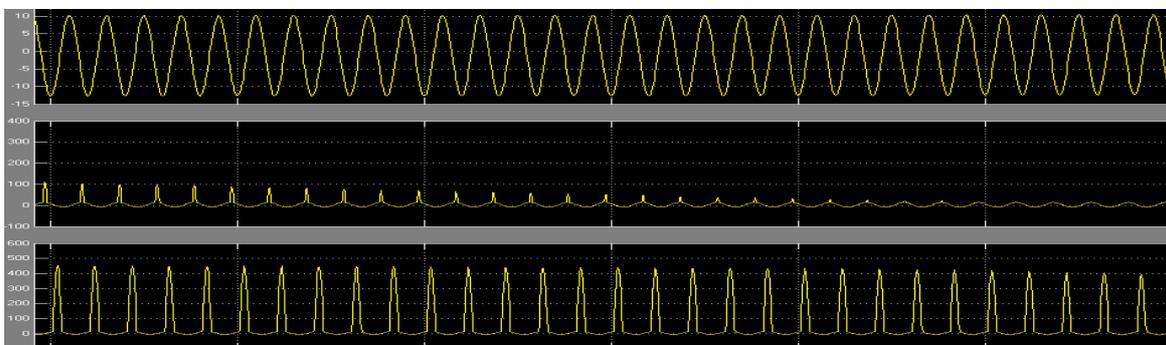


Fig 9: Current in phases R, Y and B of primary side with Sequential Switching method

IV. CONCLUSION

In this paper, effective methods are used to reduce the inrush current. In Pre-insertion resistance method by adding different value of resistance in series with transformer at primary side which mitigate inrush current. The best value of

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resistance is 238Ω at this value the inrush current reduces about 50%. But to reduce the effect of saturation of transformer core inserting the capacitor with resistance which is known as a Pre-insertion resistance with capacitor method. The best value of capacitor is $20\ \mu\text{F}$ at this value, inrush current reduces about 80%. The Sequential switching method is found to be easy to implement which has nullified inrush current approximately at their respective phases. Sequential switching method is a simple and easy method as compare to Pre-insertion resistance method and Pre-insertion resistance with capacitor method.

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