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Mitigation of Inrush Current in Load Transformer for Series Voltage Sag Compensator

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Abstract— **In the power system voltage sag become the important issue for industries and many other consumers. According to the survey 92% of the interruptions at industrial installations are voltage sag related. In various companies voltage sag may affect many manufactures and may reduce the efficiency of the system which results sufficient losses in the power system. The voltage sag compensator, based on a transformer coupled with voltage source inverter for serial connection, is among the most cost-effective solution against voltage sags. A transformer inrush may occur at the start of sag compensator. This over current may damage the inrush protection of the series connected inverter and the transformer output voltage is greatly reduced due the magnetic saturation. When the compensator restores the load voltage, the flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. This paper proposes a new technique for mitigating the inrush of the coupling transformer and preserving the output voltage for effective sag compensation.**

Keywords— voltage sag compensator, transformer inrush, voltage sags,

I INTRODUCTION

Voltage problem is considered one of the most power quality problems, because any power quality event in utility may affect the several kinds of sensitive loads connected to the power system. The voltage sag phenomenon is of short duration reduction of rms voltage caused by power system faults, variation of load and due to start of induction motors that is inductive loads. Survey records show that short duration of rms voltage and transient constitute 92% of power quality problem. Mostly the sag voltage may affect manufactures and introduce losses in the system. The most common cause of voltage sag is flow of fault current which may affect number of consumers. Voltage sag due to the faults may produce incorrect operations in the various protective devices. The voltage sag is a reduction to between 0.1 and 0.9 in rms voltage or current at a power frequency for the time period 10ms to 1 min that is 0.5 to 30 cycles. Sag may result the reduction of efficiency in the system which are sensitive to voltage variations. Voltage sag compensators become the most cost effective solution of voltage sag. These voltage sag compensators may restore the sag within a quarter cycle. Various closed loop control techniques has been proposed for voltage source inverter (VSI) based sag compensators. However in the load transformer which is coupled with VSI may subject an inrush current during the restoration of voltage sag. A technique to mitigating the inrush current is proposed and implemented in the synchronous reference frame sag compensator controller. This tech. is integrated with closed loop control on load voltage to obtain steady state of voltage. By this technique we can successfully reduce the inrush current in the load transformer and robustness of sag compensator system.

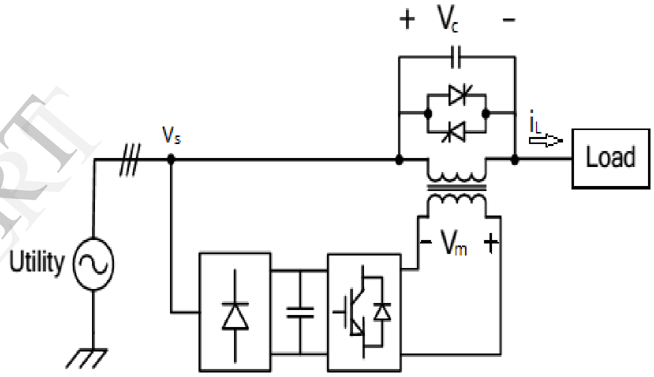


Fig. 1. Single line diagram of the series voltage sag compensator.

As shown in figure 1, the voltage sag compensator consist of three phase voltage source inverter and coupling load transformer for serial connection of the system. The compensator is bypassed by the thyristors when the grid operates normally for high efficiency. The voltage sag compensator comes into the picture when sag occurs. The voltage sag compensator injects the required voltage through the load transformer which is series in the system to protect the sensitive load effected by the sag. Before the voltage sag restoration the deforming voltage inside the load transformer may cause magnetic flux deviation and magnetic saturation may easily occur this results the inrush the transformer. This inrush may damage the over current protection of the VSI and lead to failure of compensator. This paper presents the inrush mitigation technique by the flux linkage offset of load transformer and the technique will be integrated with feedback controller of compensator.

II CONFIGURATION OF COMPENSATOR

The per phase equivalent circuit of the sag compensator are shown in figure 2. The output of the inverter is filtered by low pass filter that is inductor of transformer L_f and capacitor C_f which suppress the dc component and PWM ripples from the output of inverter voltage v_m.

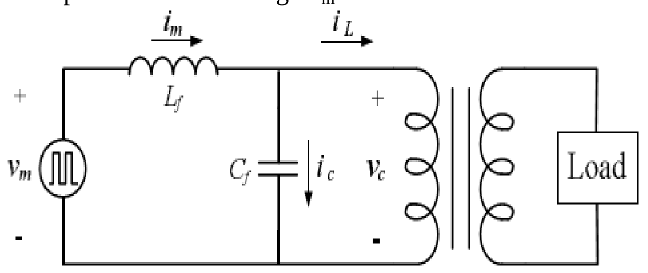


Fig. 2. Per phase equivalent circuit of the sag compensator

Equation (1) and (2) are the dynamic equations of the equivalent circuit:

$$L_f \frac{d}{dt}\begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} = \begin{bmatrix} v_{ma} \\ v_{mb} \\ v_{mc} \end{bmatrix} - \begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} \quad (1)$$

$$C_f \frac{d}{dt}\begin{bmatrix} v_{ca} \\ v_{cb} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} i_{ma} \\ i_{mb} \\ i_{mc} \end{bmatrix} - \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

Where $[v_{ma}\ v_{mb}\ v_{mc}]^T$ is the inverter output voltage, $[i_{ma}\ i_{mb}\ i_{mc}]^T$is the filter inductor current, $[v_{ca}\ v_{cb}\ v_{cc}]^T$is the compensation voltage, and $[i_{La}\ i_{Lb}\ i_{Lc}]^T$is the load current. Equation (1) and (2) are transferred into the synchronous reference frame as (3) and (4).

$$\frac{d}{dt}\begin{bmatrix} i_{mq}^e \\ i_{md}^e \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_{mq}^e \\ i_{md}^e \end{bmatrix} + \frac{1}{L_f}\begin{bmatrix} v_{mq}^e \\ v_{mq}^e \end{bmatrix} - \frac{1}{L_f}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} \quad (3)$$

$$\frac{d}{dt}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} v_{cq}^e \\ v_{cd}^e \end{bmatrix} + \frac{1}{C_f}\begin{bmatrix} i_{mq}^e \\ i_{mq}^e \end{bmatrix} - \frac{1}{C_f}\begin{bmatrix} i_{Lq}^e \\ i_{Ld}^e \end{bmatrix} \quad (4)$$

Where superscript "e" indicates the synchronous reference frame representation of this variable and ω is the angular frequency of the utility grid. Equation (3) and (4) show the cross-coupling terms between compensation voltage and filter inductor current.

III INRUSH CURRENT STUDY

When a voltage is subjected to a transformer at a period when normal steady-state flux would be at a different value from that remaining in the transformer, a current transient happens, known as magnetizing inrush current. The saturation of the magnetic core of a transformer is the key source of an inrush current transient. The saturation of the core is owing to an sudden variation in the system voltage which can be produced by switching transients, synchronization of a generator remains out of phase, outdoor faults and faults renovation. The energization of a transformer produce to the simplest situation of inrush current and the flux in the core may extent a maximum theoretical significance of two to three times the evaluated flux peak. Fig. 3 demonstrates how flux linkage and current changes. There is no straight sign that the energization of a transformer can produce an abrupt failure due to high inrush currents. Though, insulation failures in power transformers which are repeatedly energized under no load situation supports the mistrust that inrush current have a dangerous results. The transformer inrush current is the function of several approaches like the terminal voltage switching angle, the remaining flux of the magnetic core, design of the transformer, impedance of the system etc.

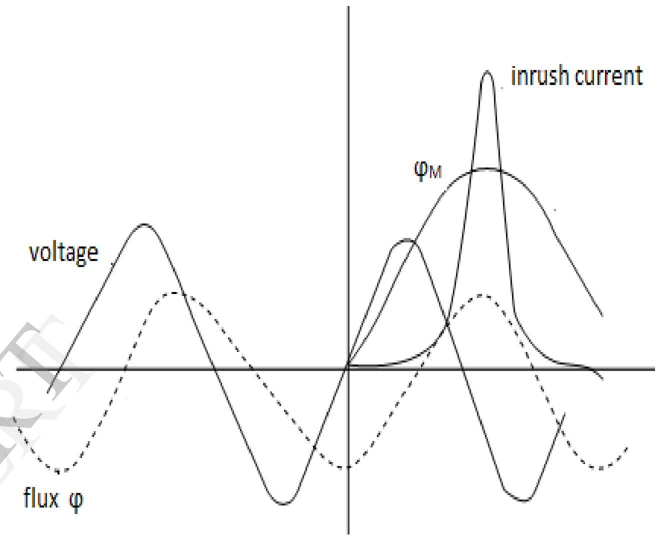


Fig. 3. Inrush current formation

The general equation that gives the amplitude of inrush current as a function of time can be expressed as:

$$i(\mathrm{t}) = \frac{\sqrt{2}V_m}{z_t} * K_w * K_s * (\sin(\omega \mathrm{t} - \varphi) - \mathrm{e}^{\frac{-(\mathrm{t}-\mathrm{t}_0)}{t}} \sin\alpha) \quad (5)$$

Where V_m is maximum functional voltage; Z_t is total impedance under inrush, as well as system; φ is energization angle; t is time; t_0 is a point at which core saturates; τ is a time constant of transformer winding under inrush circumstances; α is a function of t_0; K_w explanations for 3 phase winding connection; K_s explanations for short-circuit power of network.

A basic equation can be used to analyses the peak value of the first cycle of the inrush current. This equation is as follow:

$$i_{peak} = \frac{\sqrt{2}V_m}{\sqrt{(\omega.\mathrm{L})^2 + R^2}}\left(\frac{2.B_N + B_R - B_S}{B_N}\right) \quad (6)$$

Where V_m maximum applied voltage; L air core inductance of the transformer; R total dc resistance of the transformer; B_N standard rated flux density of the transformer core; B_R remnant flux density of the transformer core; B_S saturation flux density of the core material.

As seen from the equations (5) and (6), the charge of inrush current is dependent to the parameters of transformer and operating circumstances. So a full analysis for resulting the relations between the inrush current characteristics and these factors are needed.

IV METHODS USED FOR CONTROL

The proposed control method is shown in a block diagram in which d axis controller is not shown for your simplicity. In the block diagram full state feedback controller with inrush current technique are used. Detailed explanation are given as bellow:

A. *The Full State Feedback Scheme*

The state feedback scheme contains feedforward control, feedback control, and the decoupling control.

1) *Feedback Control*

The feedback control is used to improve the accuracy of the compensation voltage, the robustness and the distribution rejection ability against the variation in the parameters as shown in block diagram. The voltage from the capacitor v^e_{cq} is.

the inner loop voltage control and the current from the inductor i^e_{mq} is the current control in the inner loop The control of the voltage con be done by the propositional regulator with voltage command v^{e*}_{cq} respectively according to the requirement of the sag.

2) *Feedforward Control*

Feedforward control is added to the voltage control loop for enhancing the dynamic response of the voltage sag compensator and to compensate the sag voltage without making any further delay. The feedforward voltage command can be measured by joining the compensation voltage and the voltage drop across the filter inductor which is produced by the filter capacitor current.

3) *Decoupling Control*

In the block diagram the cross coupling terms and the decoupling terms is derived from the synchronous reference frame transformation and the external disturbance in the voltage compensator. These controls are used to enhance the preciseness and the distribution ability. These terms can be obtained by calculating the filter capacitor voltage, load current and the filter inductor current.

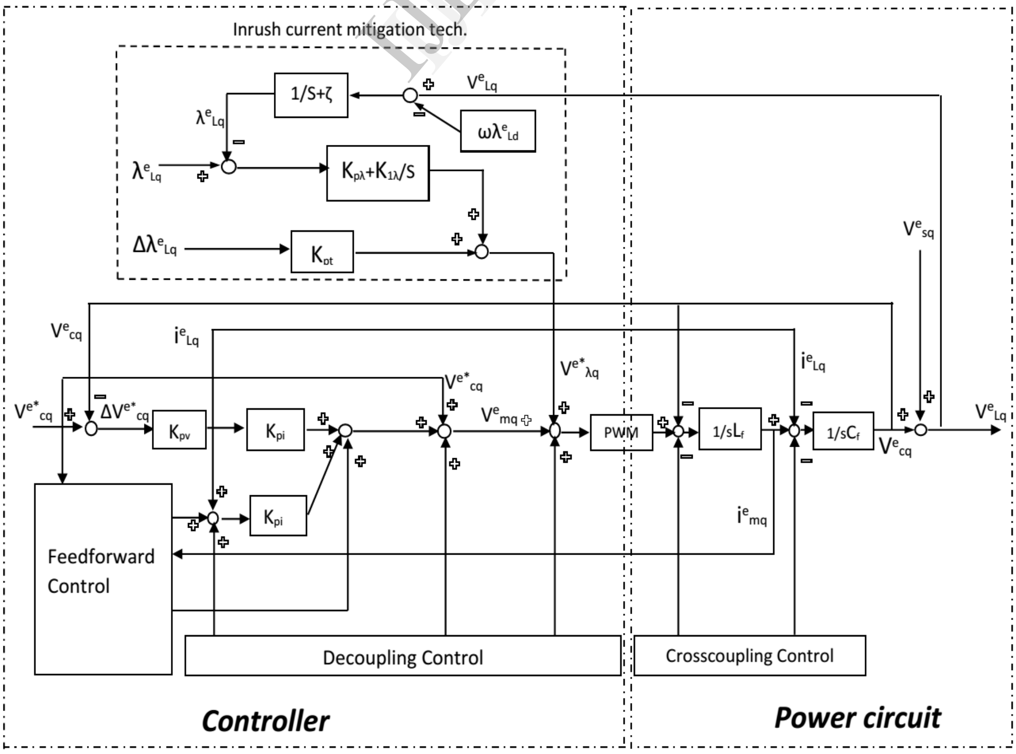


Fig.4. Block diagram of the proposed inrush current mitigation technique with the feedback control

B. The Full State Feeback Scheme

1) Flux Linkage Dc Offset

By integrating the line voltage, we can measure the flux linkage of the transformer as given in equation 7. Figure 6 shows delta/wye three phase transformer having single windings and is installed in downstream of voltage sag compensator. The linkage of the flux in the phase a-b windings is expressed as:

$$\lambda_{Lab}(t) = \int v_{Lab}(t)\,dt$$

(7)

Fig. 7 shows the line-to-line voltage through the transformer winding and the causing flux linkage attained from the voltage sag incidence to completion of voltage compensation. When voltage sags happens ($t=t_{sag}$), the controller senses the sagged voltage and inserts the essential compensation voltage at $t = t_{detect}$. The flux linkage through the voltage compensation procedure can be direct as following:

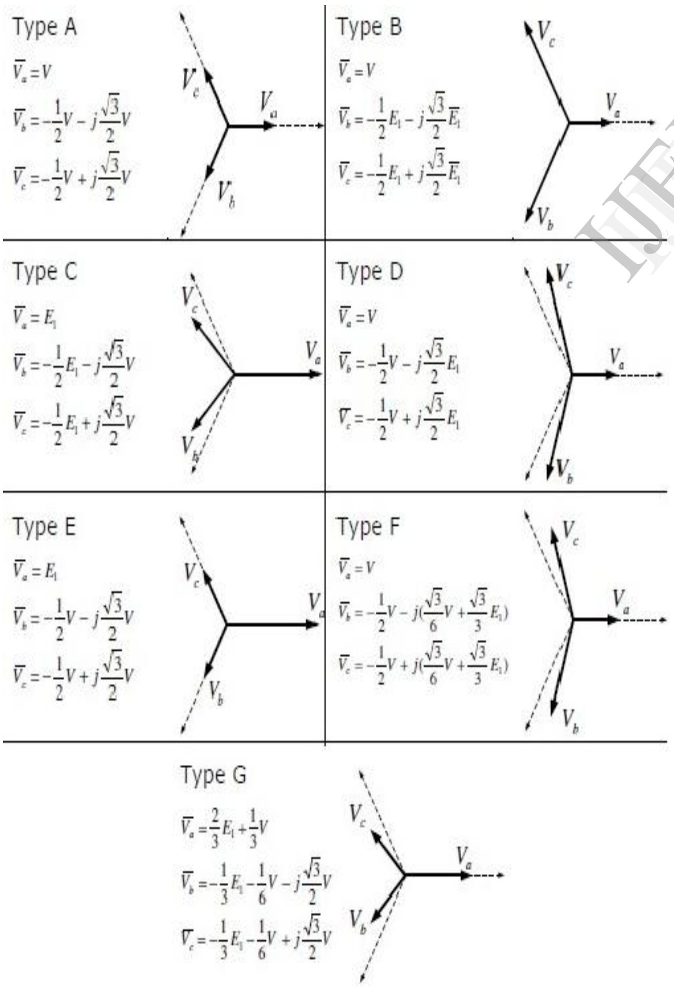


Fig. 5. Phasor diagrams of various types of voltages sags

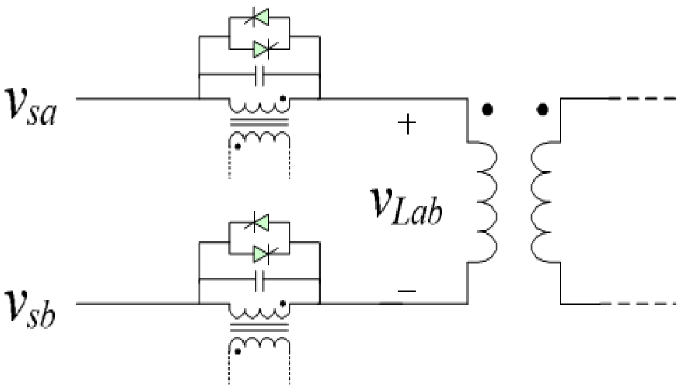


Fig. 6. Connection diagram of the proposed system and delta/wye load transformer.

$$\lambda_{Lab}(t) = \lambda_{Lab}(t)\Big|_{t=t_{sag}} \int_{t_{sag}}^{t_{detect}} v_{Lab}(t)\,dt + \int_{t_{detect}}^{t} v^{*}_{Lab}(t)\,dt \qquad (8)$$

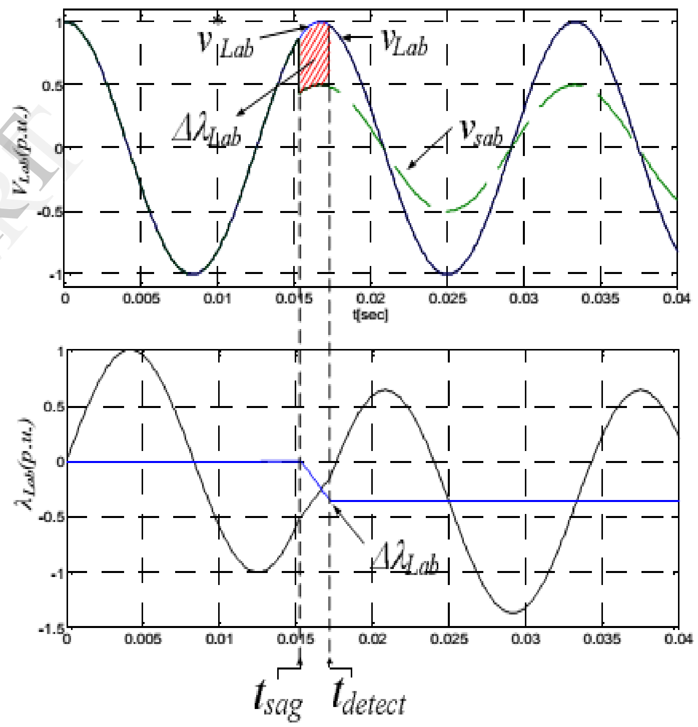


Fig. 7. Transformer voltage and corresponding transient flux linkage

Above equation can be rewritten as follows:

$$\lambda_{Lab}(t) = \lambda_{Lab}(t)\Big|_{t=t_{sag}} - \int_{0}^{t} v^{*}_{Lab}(t)\,dt + \int_{t_{sag}}^{t_{detect}} (v_{Lab}(t) - v^{*}_{Lab}(t))\,dt + \int_{0}^{t} v^{*}_{Lab}(t)\,dt \qquad (9)$$

Where V^*_{Lab} (t) is the pre-fault load voltage defined as follows:

$$v^*_{Lab}(\mathrm{t}) = \hat{V}^*_{Lab} \sin(\omega \mathrm{t} + \Phi^*_{Lab})$$

Where $\tilde{V}^*_{Lab}$ is the magnitude of load voltage, ω is the grid frequency, and Φ^*_{Lab} is the phase angle. Thus, after the voltage compensation is completed, the flux linkage can be expressed as follows:

$$\lambda_{Lab}(\mathrm{t}) = \Delta\lambda_{Lab}(\mathrm{t})\Big|_{t=t_{\mathrm{detect}}} + \frac{\hat{V}^*_{Lab}}{\omega}\sin(\omega \mathrm{t} + \Phi^*_{Lab} - \frac{\Pi}{2}) \qquad (10)$$

$$\Delta\lambda_{Lab}(\mathrm{t})\Big|_{t=t_{\mathrm{detect}}} = \lambda_{Lab}(\mathrm{t})\Big|_{t=t_{sag}} - \lambda^*_{Lab}\Big|_{t=t_{sag}} + \int_{t_{sag}}^{t_{\mathrm{detect}}} (v_{Lab}(\mathrm{t}) - v^*_{Lab}(\mathrm{t}))\,\mathrm{dt} \qquad (11)$$

$$t_{sag} \le t \le t_{\mathrm{detect}}$$

By the above equation no. 11 the flux linkage DC offset $\Delta\lambda_{Lab}$ which is obtained by the voltage sags on the transformer windings, also the flux magnitude is dependent on the depth and the duration of sags. Various voltage sags may occur the DC offset which can saturate the core of the transformer above the knee may cause inrush current. Usually the magnetic saturation knee is 1.10-1.15 p.u. of state-study flux linkage.

2) Design the Flux Linkage Estimation

The single phase transformer under no load condition is shown in figure 8, where R_1 and L_{l1} is the primary side equivalent resistor of copper loss and the equivalent leakage inductance respectively. R_c and L_m is the equivalent resistor of core loss and magnetic inductance.

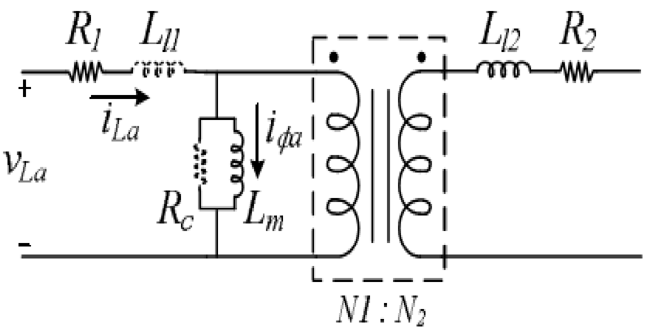


Fig. 8. Equivalent per phase circuit model of the transformer

This dynamics of the transformer equivalent circuit in Fig. 8 can be expressed as:

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = L_m \frac{d}{dt}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} + R_1 \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (12)$$

Note that for simplification the leakage inductances and the core losses are neglected.

This equation can be re-written as:

Where

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \lambda_{La} \\ \lambda_{Lb} \\ \lambda_{Lc} \end{bmatrix} + \frac{R_1}{L_m}\begin{bmatrix} \lambda_{La} \\ \lambda_{Lb} \\ \lambda_{Lc} \end{bmatrix} \qquad (13)$$

Where

$$[\lambda_{La} \quad \lambda_{Lb} \quad \lambda_{Lc}]^T = L_m [i_{La} \quad i_{Lb} \quad i_{Lc}]$$

The dynamics of the transformer flux linkages can be transformed into the synchronous reference frame as:

$$\begin{bmatrix} \lambda_{Lq} \\ \lambda_{Ld} \end{bmatrix}^e = \int (\begin{bmatrix} v_{Lq} \\ v_{Ld} \end{bmatrix}^e + \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} \lambda_{Lq} \\ \lambda_{Ld} \end{bmatrix}^e - \zeta \begin{bmatrix} \lambda_{Lq} \\ \lambda_{Ld} \end{bmatrix}^e)dt \qquad (14)$$

Where the damping ratio, $\zeta = R_1/L_m$, chooses the transient of the flux linkage. Figure 9 illustrations the flux linkage estimator under the synchronous reference frame resulting from the equation (14).

The flux linkage estimator, as presented in Fig. 9, is applied the proposed inrush mitigation technique. The proposed inrush mitigation technique contains feedback control and feedforward control.

In the feedback control loop, the flux linkage λ^e_{Lq} is produced by integrating the load voltage v^e_{Lq}. The abnormality of the flux linkage can be intended by the difference between λ^{e*}_{Lq} and the flux linkage λ^e_{Lq}. The error is controlled by a proportional-integral (PI) regulator.

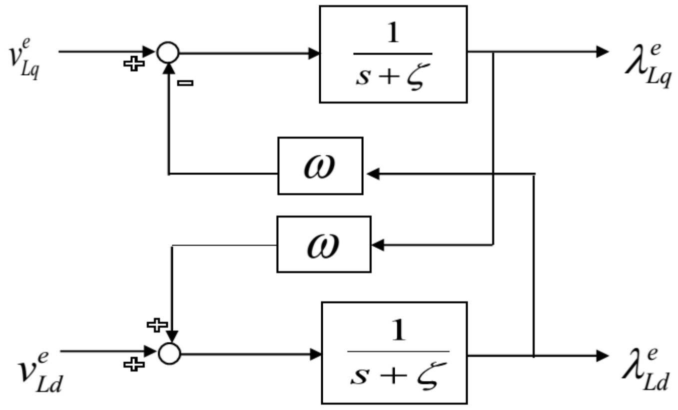


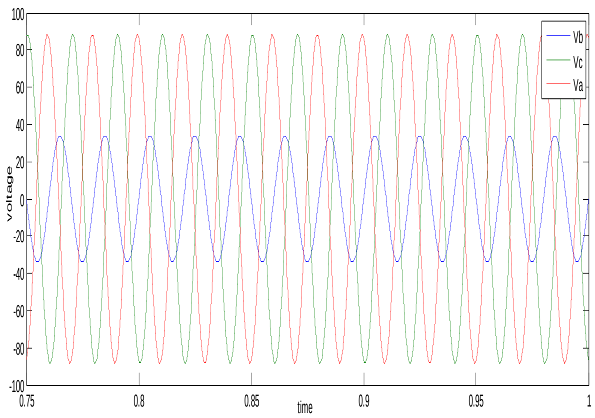
Fig. 9. The flux linkage estimator under the synchronous reference frame.

To speed up the dynamics response of the inrush current mitigation, the error between the projected flux linkage DC offset and the flux linkage command ($\Delta\lambda^e_{Lq} = \lambda^{e*}_{Lq} - \lambda^e_{Lq}$) is applied as a feedforward control term. The command is multiplied by a proportional gain K_{pt} (=1/ΔT) to fast-track the DC offset compensation throughout the compensator start transient. The control gain K_{pt} is designated according to the accepting of inrush current and the time obligation of flux linkage DC offset compensation.

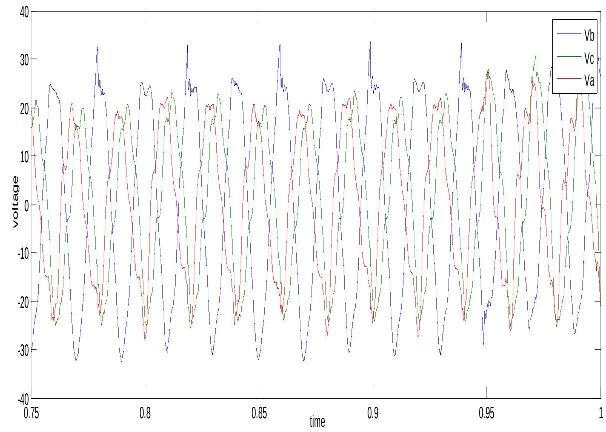
The summation $v^{e*}_{\lambda q}$ of feedback and feedforward command is added to the sag compensation voltage command v^{e*}_{mq} to create the complete command voltage of the voltage sag compensator. Thus, the projected control method indicate the voltage sag compensator to achieve an outstanding load voltage tracking and avoid the inrush current happens on the load-side transformer.

V SIMULATION RESULTS

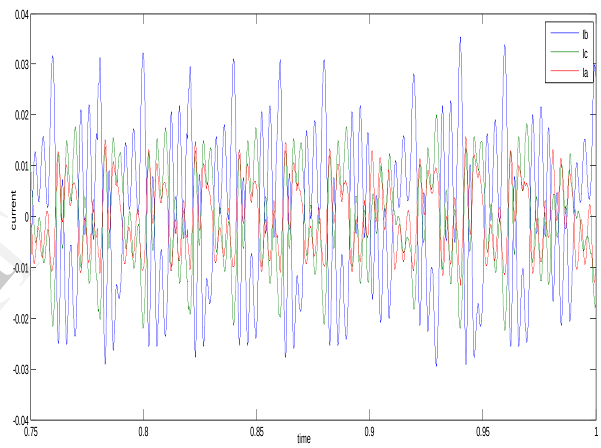
A. Without Inrush Mitigation Technique.



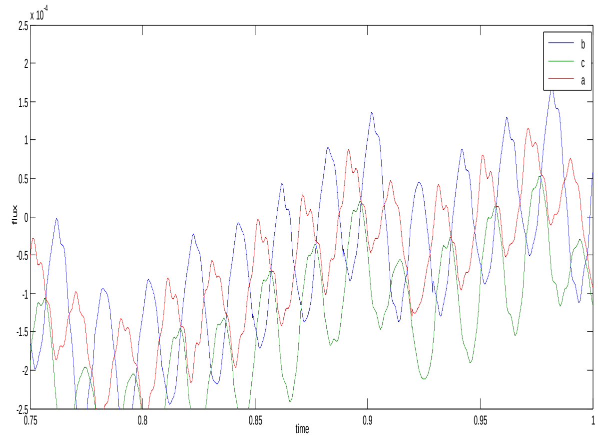
Source Voltage V_s



Load Voltage V_l

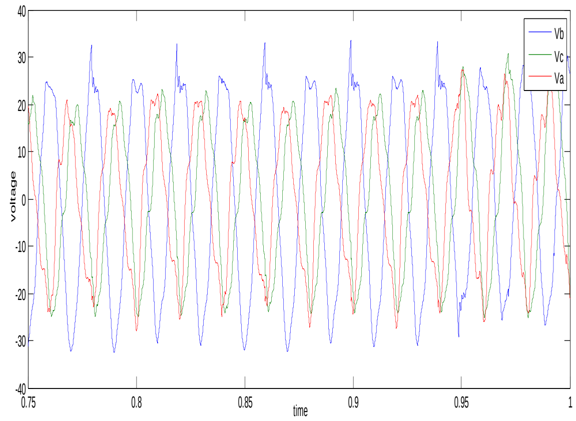


Load Current I_l

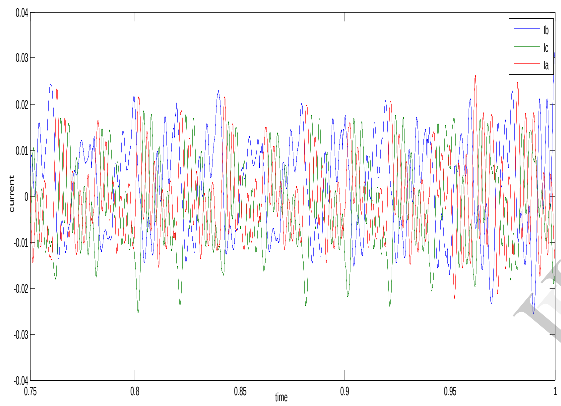


Transformer flux linkage λ_l

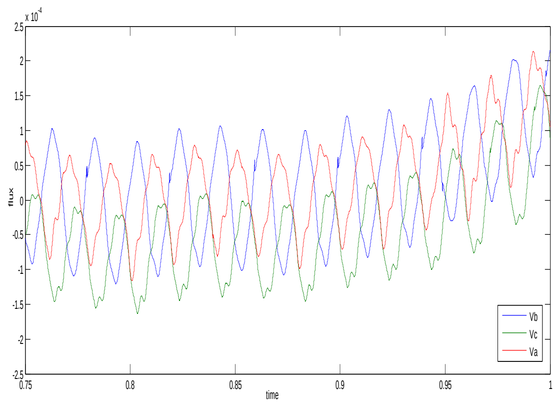
B. *With Inrush Mitigation Technique.*



Source Voltage V_s



Load Current I_l



Transformer flux linkage λ_l

VI CONCLUSION

In this paper a technique used for mitigation of transformer inrush current including with full state feedback controller to eliminate the inrush current effect at the time of voltage sag restoration in the power system. The controller provides to control the voltage, the current and the flux linkage. The method used for controller is based on the synchronous reference frame which allows the compensator to inject the sag voltage very quickly and prevents the inrush current for sensitive loads. When the voltage sag happens, the controller calculates the transient flux linkage on the bases of pre fault voltage and calculates the required voltage in real time for fast compensation and elimination of flux linkage dc offset created by voltage sag. The technique used for removal of voltage sag and the inrush current is shown in the simulation results. The projected technique can also be joined with the inrush reduction technique of the coupling transformer obtainable by the simulation results display that these two approaches take result at different steps of the voltage injection without interfering each other. The combination of these two approaches confirms a fast and perfect voltage sag compensation with minimum danger of inrush current.

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