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Mitigation Technique for Inrush Current Using Series Voltage Source Converter

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Abstract- **Voltage sag problems are the most frequently occurs in three-phase loads. When voltage sags are occurred in distribution system due to the nonlinear loads, transformers which are connected to critical loads are affected by inrush currents. Voltage sag compensator of series voltage source inverter type with transformer coupling is proposed in this paper for voltage sag compensation in power system. Flux linkage problems are occurs at time of voltage recovery from external device. Inrush currents are the severe problems, these causes failure of distribution equipments when entered into the system. At the time rectification of problem interruption in supply is occurs. In this paper an efficient inrush mitigation technique for series voltage sag compensator with feed-back controller is described. The performance of the proposed voltage compensator is verified by using MATLAB/ simulink software. Performance characteristics are described in simulation results of this paper**

Index Terms- **Inrush current mitigation, voltage sag compensator, voltage sag, flux linkage problem, PI controller, and power-quality enhancement.**

I. INTRODUCTION

Power quality issues have received much attention in recent few years. Therefore, any power quality events in the utility grid can influence a large number of manufactures. Records suggest that the voltage sag, transients, and momentary interruption constitute 92% of the power quality problems. Voltage sags often interrupt critical loads and results in substantial productivity losses. Industries are using the voltage sag compensators as one of the most cost effective ride through solutions, and most compensators can accomplish voltage restoration within a quarter cycles [9]. However, load transformer is exposed under the deformed voltages before the restoration, and the magnetic flux deviation may be developed within the load transformers. Once the load voltage is restored, the flux may further drift beyond the saturation knee of the core and lead to significant inrush current. The inrush current protection of the compensator could be easily triggered and lead to the compensation failure. Voltage sag compensator consists of a three-phase voltage-source inverter (VSI) and a coupling transformer for serial connection. When the grid is normal, the compensator is bypassed by the thyristors for high operating efficiency. When voltage sags occur, the voltage sag compensator injects the required compensation voltage through the coupling transformer to protect critical loads from being interrupted as shown in figure. Various transformer inrush reduction techniques have been presented, like controlling phase angle and the voltage magnitude, or actively controlling the transformer current. These methods could easily alter the output voltage waveforms of the converter, and is not suitable for voltage sag compensators, which demand the precise point on wave restoration of the load voltages .The style will adjust your fonts and line spacing

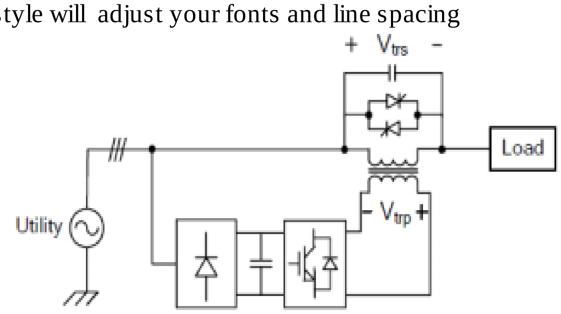

Fig.1. Simplified one-line diagram of the off-line series voltage sag compensator.

II. LITERATURE SURVEY

Many inrush mitigation techniques have been presented by many researchers like controlling power-on angle and the voltage magnitude [1-5], or actively controlling the transformer current [6-8].

These methods could easily alter the output voltage waveforms of the converter, and thus, is not suitable for voltage sag compensators, which demand precise point-on wave restoration of the load voltages. The repeated switching of distribution transformers take place due to poor generation and load shedding. The transient inrush current may be as high as ten times the full load current. Three methods are given here to avoid inrush currents in transformers and distributed lines:

1. The switching instant determines the nature and magnitude of the switching current and it is used here to control the inrush current.
2. Another method is embraced by placing a capacitor at the secondary side of the unloaded transformer connected at the sending or receiving end of the distribution line.
3. Third method is suggetsted using the distribution line as a low-pass filter.

These schemes are useful for traction transformers as well as for poorly supplied and poorly maintained distribution lines including traction line which are subjected to repeat switching. A simple and low cost method to reduce inrush currents caused by transformer energization is proposed here. The method uses a grounding resistor connected at a transformer neutral point. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series-inserted resistor and thereby significantly reduces the energization inrush currents. The presented method is much less expensive, however, since there is only one resistor involved and the resistor carries only a small neutral current in steady-state. A sequential phase energization based inrush current reduction scheme. The scheme connects a resistor at the transformer neutral point and energizes each phase of the transformer in sequence. It was found that the voltage across the breaker to be closed has a significant impact on the inrush current magnitude. This paper depicts that the idea of sequential phase energization leads to a new class of techniques for limiting switching transients. The magnetizing inrush current which occurs at the time of energization of a transformer is due to temporary over fluxing in the transformer core. Its magnitude mainly determined by switching parameters such as the resistance of the primary winding, the point-on-voltage wave (switching angle), and the remnant flux density of the transformer at the time of energization. A method is proposed which removes the requirement for rating the series injection transformers for the DVR transient switch-on period, and therefore eliminates the redundancy normally associated with their steady state operation. During the transient period at the start of voltage sag, a DVR injection transformer can experience a flux linkage that is up to twice its nominal steady-state value. This paper proposed a novel method of suppressing the inrush current of transformers. A small rated voltage source PWM converter was connected in series to a transformer through a matching transformer.

III. SYSTEM DESCRIPTION

As shown in Fig. 2, the voltage sag compensator consists of a three-phase voltage-source inverter (VSI) and a coupling transformer for serial connection. When the grid is normal, the compensator is bypassed by the thyristors for high operating efficiency. When voltage sags occur, the voltage sag compensator injects the needed compensation voltage through the coupling transformer to protect critical loads from being interrupted. However, certain detection time (typically within 4.0 ms) is needed by the sag compensator controller to identify the sag event. And the load transformer is exposed to the deformed voltage from the sag occurrence to the moment when the compensator restores the load voltage. The magnetic saturation may easily occur when the compensator restores the load voltage, and thus, results in the inrush current. The inrush current could trigger the over current protection of the compensator and lead to compensation failure. Thus, this paper introduces an inrush mitigation technique by correcting the flux linkage offsets of the load transformer.

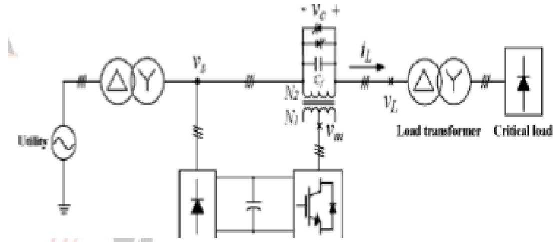

Fig.2 Simplified one-line diagram of the offline series voltage sag compensator.

The dynamics of the sag compensator can be represented by an equivalent circuit in Fig. 2. Generally, the sag compensator is rated for compensating all three-phase voltages down to 50% of nominal grid voltage. The coupling transformer is capable of electrical isolation or boosting the compensation voltage inductor of the coupling transformer is used as the filter inductor Lf and is combined with the filter capacitor C_f installed in the secondary winding of the coupling transformer to suppress pulse width modulated (PWM) ripples of the inverter output voltage V_m. The dynamics equations are as follows:

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

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

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. Equations (1) and (2) are transformed into the synchronous reference frame as the following:

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

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

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

IV. PROPOSED ARCHITECTURE

A. Inrush Current Mitigation Technique Flux linkage DC offset

The flux linkage is estimated by the measured line voltage. Figure 3 shows a single winding of the delta/wye three-phase load transformer which is installed in downstream of voltage sag compensator.

The flux linkage of the phase a-b winding is expressed as

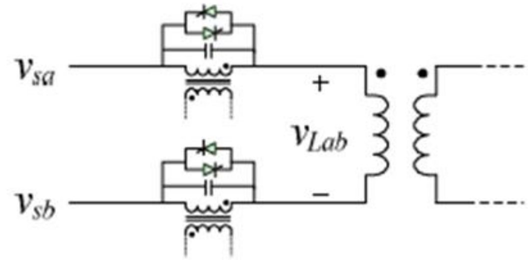

Fig.2. Connection diagram of the proposed system and delta/wye load transformer

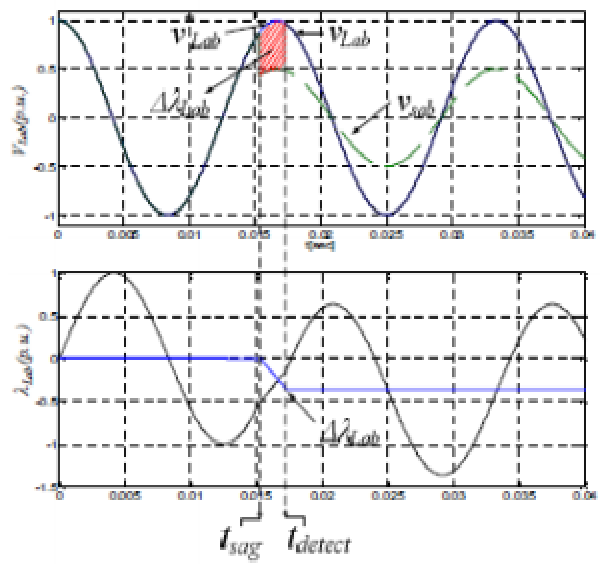

Fig.3. Transformer voltage and corresponding transient flux linkage.

Figure 3 depicts the line-to-line voltage across the transformer winding and the resulting flux linkage from the sag occurrence to completion of voltage compensation. When voltage sags occurs (t=t sag), the controller detects the sagged voltage and injects the necessary compensation voltage at t=t detect. The flux linkage during the voltage compensation process can be express as following:

$$\lambda_{Lab}(t) = \lambda_{Lab}(t)\big|_{t=t_{sag}} + \int_{t_{sag}}^{t_{detect}} v_{Lab}(t)dt + \int_{t_{detect}} v^*_{Lab}(t)dt \quad (5)$$

This equation can be re-written as

$$\lambda_{Lab}(t) = \lambda_{Lab}(t)\big|_{t=t_{sag}} - \int_0^{t_{sag}} v^*_{Lab}(t)dt + \int_{t_{sag}}^{t_{detect}} \left(v_{Lab}(t) - v^*_{Lab}(t)\right)dt + \int_0 v^*_{Lab}(t)dt \quad (6)$$

Assume the pre-fault load voltage is

$$\lambda_{Lab}(t) = \lambda_{Lab}(t)\Big|_{t=t_{sag}} + \int_{t_{sag}}^{t_{det\,ect}} v_{Lab}(t)dt + \int_{t_{det\,ect}} v^{*}_{Lab}(t)dt \tag{7}$$

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

$$\lambda_{Lab}(t) = \Delta\lambda_{Lab}(t)\Big|_{t=t_{det\,ect}} + \frac{\hat{V}^{*}_{Lab}}{\omega}\sin(\omega t + \Phi^{*}_{Lab} - \frac{\pi}{2}) \tag{8}$$

Where

$$\Delta\lambda_{Lab}(t)\Big|_{t=t_{det\,ect}} = \lambda_{Lab}(t)\Big|_{t=t_{sag}} - \lambda^{*}_{Lab}\Big|_{t=t_{sag}} + \int_{t_{sag}}^{t_{det\,ect}} \left(v_{Lab}(t) - v^{*}_{Lab}(t)\right)dt \tag{9}$$

$$for \quad t_{sag} \le t < t_{det\,ect}$$

Equation (9) states that the sagged voltages cause the flux linkage DC offset Δλ Lab on the transformer windings, and its magnitude is dependent on the depth and the duration of sags. Severe voltage sag event can drive the DC offset exceeding the magnetic saturation knee and causes high inrush current. In practical saturation, the magnetic saturation knee is usually put on 1.10-1.15 p.u. of state-study flux linkage.

V. 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, called as magnetizing inrush current. The saturation of the magnetic core of a transformer is the main source of an inrush current transient. The saturation of the core is owing to an sudden changes 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 calculated flux peak. Fig. 4 illustrates how flux linkage and current changes**.** There is no straight sign that the energization of a transformer can yields an abrupt failure due to high inrush currents. Though, insulation failures in power transformers which are repeatedly energized under no load situation suggest 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. The general equation that yields the amplitude of inrush current as a function of time can be expressed as:

$$i(t) = \frac{\sqrt{2}V_m}{z_t} * K_w * K_s * (\sin(\omega t - \varphi) - e^{\frac{-(t-t_0)}{\tau}} \sin\alpha) \tag{7}$$

Where Vm is maximum functional voltage; Zt is total impedance under inrush, as well as system; φ is energization angle; t is time; t0 is a point at which core saturates; τ is a time constant of transformer winding under inrush circumstances; α is a function of t0; Kw explanations for 3 phase winding connection; Ks explanations for short-circuit power of network. A fundamental equation can be used to analyses the peak value of the first cycle of the inrush current. This equation is as follow:

$$i_{peak} = \frac{\sqrt{2}V_m}{\sqrt{(\omega.L)^2 + R^2}}\left(\frac{2.B_N + B_R - B_S}{B_N}\right) \tag{8}$$

Where Vm maximum applied voltage; L air core inductance of the transformer; R total dc resistance of the transformer; BN standard rated flux density of the transformer core; BR remnant flux density of the transformer core; BS saturation flux density of the core material. As seen from the equations (7) and (8), 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.

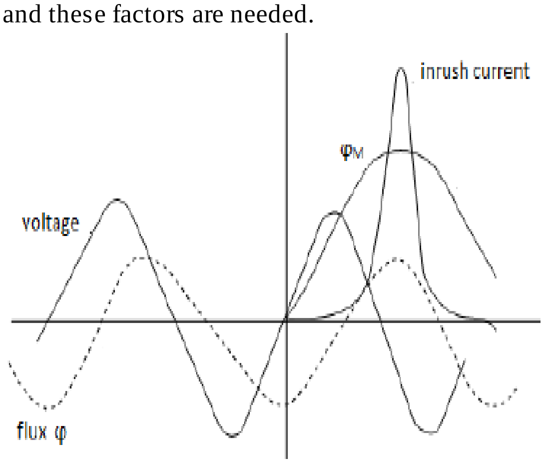

Fig.4. Inrush current formation

VI. CONCLUSION

This paper focuses on various mitigation methods for inrush current in transformers. Current significantly reduces with point on wave switching method. Increasing of the switching angle will decrease the inrush current amplitude. Results show that by increasing switching angle will decrease the inrush current amplitude at a positive remanent flux or source resistance. The effect of remanent flux on the first cycle peak current indicates that it has large changes when the remanent flux varies.

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