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Mitigation of Inrush Current of Transformer using Voltage Sag Compensator

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Abstract— In the power system voltage sag become the important issue for industries. 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 introduce sufficient losses in the power system. The voltage sag compensator, based on a transformer coupled series connected voltage source inverter, 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— Mitigation of Inrush Current in Load Transformers, Mitigation of Inrush Current using Voltage Sag Compensator, Mitigation of Inrush Current using Series Voltage Sag Compensator, Mitigation Technique for Inrush Current, Voltage Sag Compensator.

I. INTRODUCTION

Power quality issues have received much attention in recent few years. Therefore, any power quality events in the utility grid can affect a large number of manufactures. Records show 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. 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. 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 [10].

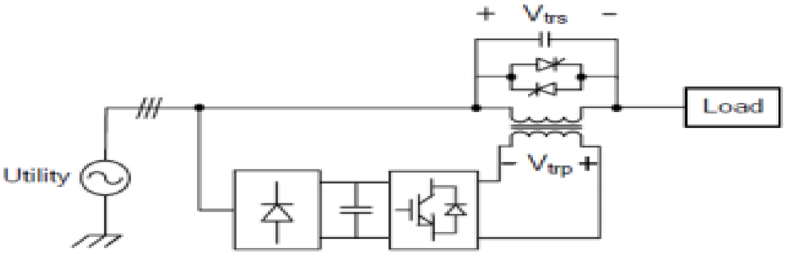

Fig.1. Simplified one-line diagram of the off-line series voltage sag compensator.

II. LITERATURE SURVEY

In the Literature survey it reveals that voltage sag is a critical problem in power system. Many inrush mitigation techniques have been presented by various 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 decides the nature and magnitude of the switching current and it is used here to control the inrush current.
2. Another method is adopted 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 proposed 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 [1]. 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 [2]. 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. In this paper it is shown that the idea of sequential phase energization leads to a new class of techniques for limiting switching transients [3]. Its magnitude mainly depends on 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 instant of energization [4]. The authors in [5] have proposed a method which removes the need for rating the series injection transformers for the DVR transient switch-on period, and therefore removes 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 [8] 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 required compensation voltage through the coupling transformer to protect critical loads from being interrupted. However, certain detection time (typically within 4.0 ms) is required 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 overcurrent 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.

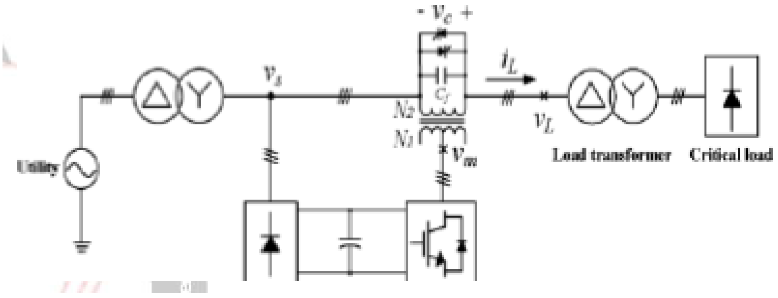

Fig.2 Simplified one-line diagram of the offline series voltage sag compensator.

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 expressed as follows:

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

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

Where, [vma vmb vmc]T is the inverter output voltage, [ima imb imc]T is the filter inductor current, [vca vcb vcc]T is the compensation voltage, and [iLa iLb iLc]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**

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. 4 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. The general equation that gives 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 basic equation can be used to analyses the peak value of the first cycle of the inrush current. This equation is as follow:

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

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 with the relations between the inrush current characteristics and these factors are needed.

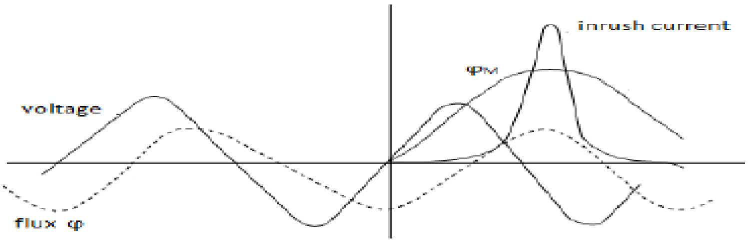

Fig.4. Inrush current formation

V. PROPOSED CONTROL METHOD

Figure 5 shows the block diagram of the proposed control method. Note that the d-axis controller is not shown for simplicity. The block diagram consists of the full state feedback controller and the proposed inrush current mitigation tech. Detail explanation given in the following section.

Fig. 5. Block diagram of the proposed inrush current mitigation technique with the sate feedback control.

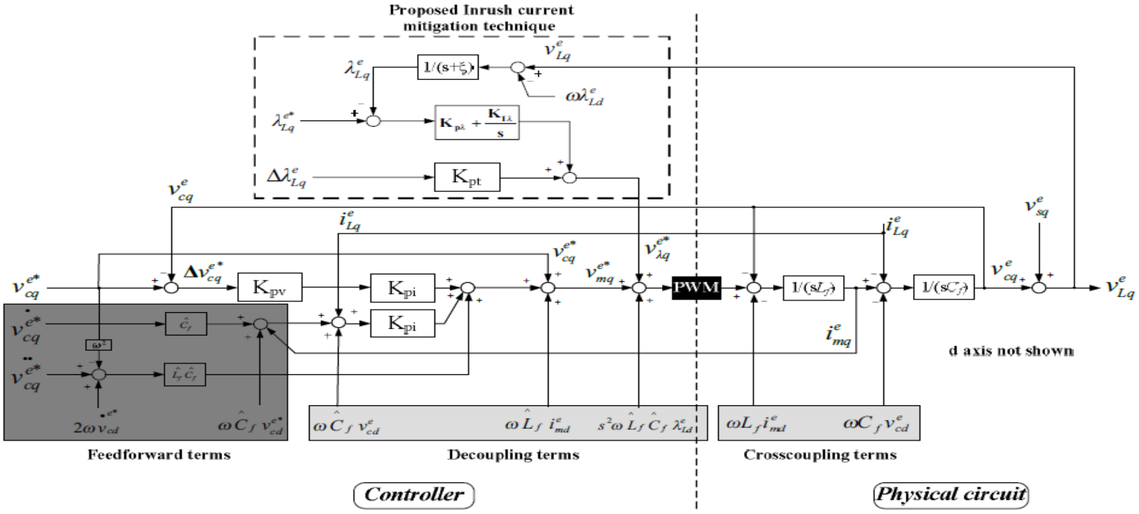

Fig. 5. Block diagram of the proposed inrush current mitigation technique with the state feedback control.

The full state feedback scheme

The state feedback scheme includes feedback control, feed forward control and decoupling control.

1) Feedback control

The feedback control is utilized to improve the preciseness of compensation voltage, the disturbance rejection capability and the robustness against parameter variations. As in Fig. 3, the capacitor voltage $v^e_{cq}$is the voltage control in the outer loop and the inductor current $i^{e}_{mq}$is the inner current control. The voltage control is implemented by a proportional regulator with voltage command v^{e*}_{cq} respectively produced by the voltage sag scheme.

2) Feed forward control

To improve the dynamic response of the voltage sag compensator, the feed forward control is added to the voltage control loop to compensate the load voltage immediately when voltage sag occurs. The feed forward voltage command is can be calculation by combining the compensation voltage and the voltage drop across the filter inductor which is produced by the filter capacitor current.

3) Decoupling control

Since cross coupling terms derived from the synchronous reference frame transformation and the external disturbances exists in the physical model of voltage sag compensator, the control block utilizes the decoupling control to improve the accuracy and the disturbance rejection ability. Figure 3 shows the decoupling terms is produced by measuring the load current, filter capacitor voltage and the filter inductor current. The cross coupling terms in physical model can be eliminated completely.

CONCLUSION

An inrush current mitigation technique based on the flux linkage close-loop control has been presented for the sag compensator system in this paper. This synchronous reference frame-based method can precisely estimate the flux linkage deviation introduced by the deformed sag voltages within the load transformer, and calculate the required voltage for correcting such deviation in real time. Thus, the risk of inrush current of the load transformer can be successfully avoided as the flux linkage deviation is neutralized once the sag compensator engages. The presented method utilizes the existing voltage and current sensor signals, and thus, it can be easily integrated with the voltage and current control of the sag compensator. Another method for controlling voltage sag and flux saturation in transformers used by a DVR system which uses fuzzy logic controller to compute the compensating voltage. This ensures that the compensating voltage is always at a proper level.

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