Inrush Current Mitigation Methods of Load Transformer For Series Voltage Sag Compensator

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Abstract - According to survey result 92% of the interruption at industrial as well as industrial installations are related to voltage sag. In the whole power system interruption due to voltage sag become the very important issue for industrial installations & many other consumers. In the various industries interruption due to voltage sag may largely affected many manufactures & may causes the reduction of efficiency of the system. The series voltage sag compensator with series coupled transformer & series connected voltage source inverter, is among the most superior cost effective solution against voltage sag. In the event of voltage sags of transformers are exposed to the change in voltage & DC offset will occur in its flux linkage. The flux linkage will be driven to the level of magnetic saturation & severe inrush current occurs when the compensator restores the load voltage. The interruption of compensator because of its own over current protection due to these eventually the compensation fails & critical loads are interrupted by the voltage sag.

The successful application of SVPWM for a three phase VSI and it is the standard PWM techniques to utilize the DC-AC power conversion. A solution to have harmonic free mitigation in high power converters is to use PWM control Techniques.

Instead of having a continuous pulse as in classical square wave inverter, multiple pulse in the output can have control over harmonic content and the rms value of the output voltage. In SVPWM, the angular position of the pulse varies in sine fashion with the injected third harmonic voltage component as the control signal. SVPWM technique having advantages such as high output quality, less THD, low distortion and low rating filter component. This paper proposed a reduction of inrush current of load transformer with reduction of harmonic content in the output by various new techniques with effective voltage sag compensation.

Keywords: - SVPWM- Space vector pulse width modulation, PWM-Pulse width modulation, THD-Total harmonic distortion, VSI-Voltage source inverter.

INTRODUCTION

In modern power system reliability and stability are considered to be very important issues. Stability of the system can be achieved by enhancing the power quality. Power quality deals with several issues and problems in distribution power system, maintaining the power quality can be beneficial for both customer and utility. As the system is increasing and is a vast network power quality is main issue to be considered for increasing efficiency, stability and
reliability. Power quality may be affected by voltage sag, voltage swell, harmonics, transients, voltage fluctuation, dc offset, interruptions, noise etc. Power quality issues have received much attention in recent years. In many countries, high-tech manufacturers concentrate in industry parks. Therefore, any power quality events in the utility grid can affect a large number of manufacturers. Records show that voltage sag, transients and momentary interruption constitute 92% of the power quality problems. Inrush current, input surge current or turn surge is the highest, immediate input current drawn by an electrical appliance when first turned on. Magnetizing inrush current in transformer is the current which is flow through a transformer at the time of stimulating the transformer. This current is momentary in nature and exists for hardly milliseconds. The inrush current may be up to 10 times more than usual rated current of transformer. Even though the magnitude of inrush current is so large but it generally does not produce any stable defect in transformer as it exists for very small time. But still inrush current in power transformer is a trouble, because it interferes with the action of circuits as they have been designed to function. Some effects of high inrush contain nuisance fuse or breaker interruptions, as well as arcing and malfunction of primary circuit components, such as switches. High magnetizing inrush current in transformer also require over-sizing of fuses or breakers. one more side effect of high inrush is the introduction of noise and deformation back into the mains.

In this an inrush issue of load transformers under the operation of the sag compensator is presented. An inrush mitigation technique is proposed and implemented in a sag compensator controller. The proposed technique can be integrated with the conventional closed-loop control on load voltages. The new integrated control can successfully reduce inrush current of load transformers, and improve the disturbance rejection capability and the robustness of the sag compensator system. Laboratory test results are presented to validate the proposed technique. As shown in Fig. 1, 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 sensitive loads from being interrupted by sags. However, certain detection time (typically within 4ms) 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. Also its short duration, the deformed voltage causes magnetic flux linkage deviation inside the load transformer, and magnetic saturation may easily occur when the compensator restores the load voltage, thus results in inrush current. The inrush current could trigger the overcurrent protection of the compensator and lead to compensation failure thus this paper proposes
inrush mitigation technique by correcting the flux linkage offsets of the load transformer. This technique can be seamlessly integrated with the state feedback controller of the compensator.

![Diagram](image)

**Fig. 1. Simplified One Line Diagram Of The Off-Line Series Voltage Sag Compensator**

I. FUNDAMENTALS OF INRUSH CURRENT

The magnitude of the inrush current depends on the point on the AC wave the transformer is switched on.

- If turn-on occurs when the AC voltage wave is at its peak value, there will be no inrush current drawn by the transformer. The magnitude of the current in this case will be at normal no load value.
- If at turn-on, the AC wave is going through its zero value, then the current drawn will be very high & exceed the saturation current.

A. Inrush current can be divided in three categories: -
- Energization inrush current
- Recovery inrush current
- Sympathetic inrush current

B. There are some negative side effects of inrush current
- 1) The protecting devices for overloads and internal faults may incorrectly operate and isolated the transformer.
- 2) The windings are exposed to mechanical stresses that can damage the transformer.
- 3) power-quality problems may arise: high resonant harmonic over voltages and voltage sags.
- 4) The inrush current affects the magnetic property of the core even if the transformer has no load with its secondary is open circuited.

II. INRUSH CURRENT MITIGATION METHODS

1. PWM control method
2. SVPWM control method.

1. PWM control Method

The PWM control is employed for generating a three phase AC output from the DC link of the DBR (Diode bridge rectifier). Output voltage from an inverter can also be adjusted by exercising a control within the inverter itself. The most efficient method of doing this is by pulse-width modulation control used within an inverter. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most popular method of controlling the output voltage and this method is termed as Pulse-Width Modulation (PWM) Control. PWM inverters are quite popular in industrial applications.
techniques are characterized by constant amplitude pulses. The width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonic content.

The different PWM techniques are as under:

A. Single-pulse modulation
B. Multiple pulse modulation
C. Sinusoidal pulse width modulation
   (Carrier based Pulse Width Modulation Technique).

2. Space vector PWM Method

In the SVPWM the two most widely used PWM schemes for multilevel inverters are the carrier-based sine-triangle PWM (SPWM) technique and the space vector PWM (SVPWM) technique. These modulation techniques have been extensively studied and compared for the performance parameters with two-level inverters. The SPWM schemes are more flexible and simpler to implement, but the maximum peak of the fundamental component in the output voltage is limited to 50% of the DC link voltage, and the extension of the SPWM schemes into the over-modulation range is difficult. In SVPWM schemes, a reference space vector sampled at regular intervals to determine the inverter switching vectors and their time durations, in a sampling interval. The SVPWM scheme gives a more fundamental voltage and better harmonic performance compared to the SPWM schemes. The maximum peak of the fundamental component in the output voltage obtained with space vector modulation is 15% greater than with the sine-triangle modulation scheme. But the conventional SVPWM scheme requires sector identification & look-up tables to determine the timings for various switching vectors of the inverter, in all the sectors. This makes the implementation of the SVPWM scheme quite complicated. A simplified method, to determine the correct offset times for centring the time durations of the middle inverter vectors, in a sampling interval, is presented, for the two-level inverter. The inverter leg switching times are calculated directly from the sampled amplitudes of the reference three-phase voltages with considerable reduction in the computation time determine the correct offset times for centering the time durations of the middle inverter vectors, in a sampling interval, is presented, for the two-level inverter. The inverter leg switching times are calculated directly from the sampled amplitudes of the reference three-phase voltages with considerable reduction in the computation time.

The space vector PWM control is employed for generating a three phase AC output from the DC link of the DBR (Diode bridge rectifier). Space vector is employed as it is an advanced topology from the conventional PWM techniques. Space vector PWM technique is an advancement of sinusoidal PWM as the pulses produced by digital switching of the fundamental waveform. Considering six switch operation we divide the VSI into two parts as upper part and lower part. The upper part contain the switches S1 S3 & S5 leaving the lower part of the VSI with S2 S4 & S6.
The state of the switches are either to be ON or OFF i.e., two states. The number of possible switching states are given as $2^3 = 8$. The 8 switching states are given below:

Table 1.1: Switching states

<table>
<thead>
<tr>
<th>SWITCH</th>
<th>S1</th>
<th>S3</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st MODE</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2nd MODE</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3rd MODE</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4th MODE</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5th MODE</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6th MODE</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7th MODE</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8th MODE</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

In the above mentioned 8 switching modes the first and the last switching states are completely OFF and ON which is not applicable. We only consider the six states from 1st to 6th eliminating 0 and 7th mode. The last three switching states are the compliment of first three switching states, which concludes that we have to only generate the three switching states i.e., 1st, 2nd, and 3rd. The other switching states i.e., 4th, 5th and 6th are generated by applying a NOT gate to the previous modes. A simple hexagonal representation of switching pattern is shown fig. 4 below which can be called as Space vector Trajectory.

The signal generation of space vector is compared to the triangular waveform to generate three PWM pulses to which NOT gates are given to get the other three pulses. The control signal of space vector PWM is given below fig. 3.
IV. SIMULATION AND RESULTS

The test system in designed in MATLAB Simulink is shown below in fig. The simulation is run for 3 seconds with switching of thyristors with series transformer starting from 1 second.

A. Simulation with proposed mitigation technique (PWM)

Fig 5. Simulation Model With Mitigation Technique (PWM)

Output waveform

B) Output Load Voltage

Fig 7. Load Voltage Waveform

C) Output load current

Fig 8. Load Current Waveform

A. Simulation with Proposed Mitigation Technique (SVPWM)

Fig 10. Simulation Model With Mitigation
I. Offline mitigation technique (SVPWM)
(At 0.3sec load connected without compensation, at 1 sec compensation on, from 1 to 1.5 sec load is disconnected, at 2 sec & 2.3 sec load 2&3 connected with compensation)

II. Online Mitigation technique (SVPWM)
(At 0.3sec load is connected)
a) Output load voltage

Fig. 12. Output Load Voltage Waveform
d) Output load current waveform

Fig. 14. Load current waveform

Fig. 16. Output Load Voltage Waveform
VI. Harmonics Analysis

Analytical comparison between different mitigation method are as follows:

- Harmonics analysis with PWM control method

![Fig 19 THD Analysis With Mitigation By Using PWM](image1)

- Harmonics analysis with SVPWM control method

![Fig 20 THD Analysis With Mitigation By Using SVPWM Method](image2)

<table>
<thead>
<tr>
<th>Sr.no</th>
<th>Mitigation method</th>
<th>THD value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PWM</td>
<td>4.17%</td>
</tr>
<tr>
<td>2</td>
<td>SVPWM</td>
<td>1.94%</td>
</tr>
</tbody>
</table>

VIII. CONCLUSION

- We have studied, designed and simulate inrush mitigation technique of load transformer for series voltage sag compensator with different compensator technique and found that the SVPWM technique is better over PWM technique and system goes on improving the performance.
We also have done analytical comparison of pulse width modulation (PWM) and space vector pulse width modulation (SVPWM) on the basis of total harmonic distortion (THD) and it is found that SVPWM control technique offers less harmonic distortion as compare to PWM control technique.

REFERENCES