This paper presents analysis and performance of a mitigation device for compensation of voltage sag and voltage swell disturbances. The device is designed with a fast switching IGBT operating in ac chopper mode, to regulate the primary voltage of a transformer with the principle of time-ratio control technique and maintain the load voltage at desired magnitude. Peak voltage measurement using two adjacent samples of voltage is adopted for instantaneous detection of voltage sag/swell. The advantages of less number of switching devices and high frequency harmonic currents which are easy to filter can be gained in this suggested control technique. Also the compensating device does not require energy storage such as a capacitor or a battery. Performance of the device is presented through simulation analysis for mitigation of various percentages of sag due to faults and induction motor starting, and swells due to capacitor switching. Experimental results obtained from a prototype model are presented to validate the performance of the device.

Keywords: AC chopper, STATCOM, DVR, power quality, voltage sag, voltage swell

1. INTRODUCTION

Voltage sags occur on utility systems both at distribution voltages and transmission voltages. Voltage sags which occur at higher voltages will normally spread through a utility system and will be transmitted to lower voltage systems via transformers. Starting of large motors or electrical faults inside the facility result to voltage sags within an industrial complex without any influence from the utility system. If electrical equipment fails due to overloading, cable faults etc., protective equipment will operate at the sub-station and voltage sags will be seen on other feeder lines across the utility system. Thunderstorms and lightning strikes cause a significant number of voltage sags. Among the other power quality disturbances, voltage sags are considered to be the most significant and critical [1-4]. Voltage sag can cause serious problem to sensitive loads that use voltage-sensitive components such as adjustable speed drives, process control equipment, and computers. Voltage swell in the distribution is caused during capacitor switching and sudden removal of load. There are a number of alternative solutions available for the correction of voltage sag and swell.

D-STATCOM has emerged as a promising device to provide not only for voltage sag mitigation but a host of other power quality solutions such as voltage stabilization, flicker suppression, power factor correction and harmonic control [5-8]. It consists of a voltage source inverter capable to provide fast capacitive and inductive compensation and is able to control its output current independently of the system voltage. This feature of the compensator makes it highly effective in improving the transient stability. Another device that is commonly used as a solution to voltage sag is the dynamic voltage restorer (DVR) [9-12] which employs series voltage boost technology using solid state switches to correct the load voltage amplitude as needed.

D-STATCOM and DVR both require a capacitor as the energy storage device for
supplying the dc power to the inverter. This capacitor voltage has to meet the losses in the inverter and supply power to the load during voltage disturbance. An additional feedback in the control circuit or rectifier is normally employed to maintain the capacitor voltage constant during the operation of DVR. Research is in progress to improve the performance of these mitigating devices by using multi-pulse principle [13-15], multi-level technique [16-18] and other techniques [19-21]. In all these cases, performance improvement is achieved by increase in the number of switching devices or capacitors and hence, the size and complexity of the circuit increases.

In this paper a mitigation device is presented for supporting both voltage sag and voltage swell with the principle of step-up voltage injection. This is achieved by using a fast acting IGBT switch [22, 23] and an autotransformer combination. The output voltage of the controller is varied with PWM pulses generated on time-ratio control technique. This device has less switching devices and hence reduced gate drive circuit size, but has the capability to supply the required undistorted load voltage and currents. Simulation of the compensator is performed using PSCAD/EMTDC and performance results are presented. Experimental results of a prototype testing are also given to validate the control algorithm and simulation results.

2. VOLTAGE SAG/SWELL COMPENSATION TECHNIQUE

Block diagram of the system with mitigation device for compensation of voltage sag and swell is shown in Fig. 1. It consists of bypass switch, PWM switched autotransformer and a control logic circuit. Voltage sag/swell compensator (VSSC) consists of a PWM switched power electronic device, operating in ac chopper mode, connected to an autotransformer in shunt with the load.

Under normal condition, power flow to the load is through the bypass switch consisting of fast switching thyristors connected in anti-parallel. Rise or fall in the supply voltage magnitude due to a voltage disturbance is detected by the sag/swell detection block in Fig. 1 using peak measurement technique. It generates a logic signal (N/D signal) to control the direction of power flow to the load. When a sag or swell occurs, control circuit is activated by the N/D signal and gate pulses to the bypass switch are inhibited. VSSC turned on by the gating pulses adjusts the voltage to reference value and maintains constant power supplied to the sensitive load.

![Block diagram of the voltage sag/swell mitigation scheme.](image)

Fig. 1. Block diagram of the voltage sag/swell mitigation scheme.

The detailed configuration of VSSC block in Fig. 2 consists of an IGBT switch (SW) used as power electronic device to inject controlled voltage into the line equal to the desired load voltage. Four power diodes (D1 to D4) are connected to SW controls the direction of
power flow and connected in ac voltage controller configuration. The sensitive load is connected to this controller through an autotransformer. This combination with a control circuit operating on time-ratio control technique maintains nominal rms load voltage.

Phase angle control technique applied for output voltage regulation introduces a large third harmonic component and introduces phase angle delay in the load current. This requires a large rated filter circuit and a pf correcting capacitor. In this paper, time-ratio control technique is used to overcome the above problem. Time-ratio control technique employs symmetrical angle pulse width modulation with symmetrically displaced pulses within the sinusoidal voltage waveform. The advantages of unity displacement factor and high frequency harmonic currents which are easy to filter can be gained in this control technique.

Principle of operation of voltage sag/swell mitigation device is based on ac-ac converter operation shown in Fig. 3(a) with PWM pulses supplied to fast-acting switch SW based on time-ratio control technique. The duty ratio \( K \) of gate pulses \( U_g \) in Fig. 3(b) is adjusted by varying the dc reference voltage \( U_{\text{control}} \). Output voltage of the controller shown in Fig. 3(c) and its rms value is adjusted to desired magnitude by varying the on-period of each pulse for a given input voltage.

![Fig. 2. Power circuit of voltage sag and swell compensator](image)

![Fig. 3. Principle of ac voltage controller (a). Controller circuit, and (b). Voltage waveforms and switching angles](image)

Controller output voltage contains the fundamental and odd harmonic components with
even harmonics absent due to waveform symmetry. Let the input voltage

\[ U_s = \lambda U_m \sin \omega t \]  

(1)

where \( \lambda \) varies from 0 to 1 for voltage sag condition and \( \lambda > 1 \) for voltage swell condition, \( U_m \) is the peak value of nominal input voltage and \( \omega \) is the fundamental frequency in rad/s. Fourier analysis of output voltage is given by

\[ U_{on} = \frac{2}{\pi \sqrt{2}} \int_{a_1, a_2, \ldots, a_{2N}} (\lambda U_m \sin \omega t) \sin n\omega t \, dt, \]

(2)

where \( n = 1, 3, 5, \ldots \) is the harmonic number, \( N \) = Number of pulses per half-cycle of output voltage and \( a_1, a_2, a_3, \ldots, a_{2N} \) are the switching angles. Fig. 3(b) shows the output voltage for \( N = 4 \).

The switching angles are determined by the duty cycle (or time ratio, \( K \)) as

\[ K = \frac{t_{on}}{t_{on} + t_{off}} \leq 1.0 \]

(3)

where \( t_{on} \) = on-period of IGBT and \( t_{off} \) = off-period of IGBT of each pulse.

For a wave starting with zero with \( N \) pulses and \( (N+1) \) gaps per half-cycle, the firing pulses are given by

\[ \alpha_{on} = \pi \cdot \frac{K}{N + 1 - K} \]

(4)

and

\[ \alpha_{off} = \pi \cdot \frac{1 - K}{N + 1 - K} \]

(5)

where \( \alpha_{on} \) and \( \alpha_{off} \) are the conduction and off angles of the switch.

Then the possible firing angles are given by

\[ \alpha_p = \frac{p - (p \mod 2)}{2} \cdot \left[ (\alpha_{on} + \alpha_{off}) + (p \mod 2) \right] \cdot \alpha_{off} \]

(6)

where \( p = 1, 2, 3, \ldots, 2N \).

Voltage \( U_p \) is controlled by the duty cycle of the controlled switch SW. Fig. 4(a) shows the plot of fundamental component of the load voltage and duty cycle for \( \lambda = 0.9 \) to 0.4. \( \lambda < 1 \) indicates voltage sag condition at the input of ac voltage controller. Fig. 4(b) shows the control of output \( U_p \) for the case \( \lambda > 1 \). When \( K = 1 \), output voltage is equal to input voltage of the ac voltage controller.

Considering a static RL-load connected at the output of the ac voltage controller, the current drawn by the load due to switching operation of the ac voltage controller also contains the harmonics given by

\[ I_{on} = \frac{\lambda U_{on}}{\sqrt{R^2 + (n\omega L)^2}} \angle \left( -\tan^{-1} \frac{n\omega L}{R} \right) \]

(7)
RMS load voltage \( U_L = \left[ \sum_{n=1}^{\infty} U_{on}^2 \right]^{1/2} \) \( \quad (8) \)

RMS load current \( I_L = \left[ \sum_{n=1}^{\infty} I_{on}^2 \right]^{1/2} \) \( \quad (9) \)

Fig. 4. Plot of Fundamental voltage magnitude v/s Duty ratio (a). For various sag voltages \( \lambda < 1 \) and (b). For various voltage swell magnitudes \( \lambda > 1 \)

The advantage offered by time-ratio control technique is that the fundamental component in load voltage changes linearly with \( K \) and for \( 0 \leq K \leq 1 \), the fundamental component in the load voltage can be controlled from zero up to full supply voltage. The ac voltage controller operation gives discontinuous voltage and currents. Hence filter has to be employed to obtain sinusoidal voltage and current.

3. ISSUES AND DESIGN OF SAG/SWELL COMPENSATOR

Voltage event considered for analysis are heavy load injection and faults resulting in voltage sag, and load rejection causing voltage swell. The voltage sag/swell compensator in Fig. 2 acts during a voltage event when input voltage \( U_5 \) is less than \( \pm 10\% \) of normal value. This section describes design issues of VSSC to maintain voltage at the sensitive load constant to desired value.

a. Detection and control of voltage event

Sag/swell detection block of Fig. 1 continuously monitors the supply voltage and generates a logic signal \( (N/D \) signal) when a disturbance is detected. Fig 5(a) shows the circuit of sag/swell detection block. A low pass filter is employed to remove the transients and harmonics from the supply. Peak value of the fundamental voltage \( U_m \) is then estimated as

\[
U_m = \frac{U_{sample}}{\sin(2 * pi * f_0 * samplecount * samplingperiod)} \] \( \quad (10) \)
Fig. 5. Peak detection of the waveform

Fig. 5(b) shows the peak estimation of voltage signal when a heavy load is connected to the system. Change in voltage is identified instantaneously which helps in fast mitigation action of the compensator. A high N/D logic signal is generated when there is a change in supply voltage magnitude by more than ±10% of normal value. Now the bypass switch is turned OFF and control circuit shown in Fig. 6(a) is activated.

Rms value of load voltage $U_L$ is compared with reference rms value (1 pu) in the control circuit. PI-controller is employed to generate control voltage $U_{\text{control}}$ proportional to error voltage $U_{\text{err}}$. Fig. 3(b) shows the generation of gate pulses $U_G$ by comparing $U_{\text{control}}$ with carrier frequency signal (triangular voltage, $U_{\text{ref}}$).

Fig. 6(a). Time-ratio control circuit, and (b). Plot of duty ratio v/s supply voltage during sag

The output voltage $U_p$ is a function of duty ratio $K$ of the PWM switch $SW$ as given by (2) to (6). PI-controller gain is adjusted to obtain output voltage of the ac voltage controller $U_p$ equal to 0.5 pu of normal load voltage for any value of input voltage during voltage event. From Figs. 4(a) and (b) it can be seen that duty ratio $K>0.5$ for voltage sag event ($\lambda<1$) and $K<0.5$ for voltage swell event ($\lambda>1$). Plot of duty ratio with different input voltages is shown in Fig. 6(b) for the case of voltage sag varying from 10% to 50%. Here sag voltage represents the remaining voltage at the supply during sag condition. These values of $K$ obtained from Fig. 4(a) will maintain $U_p = 0.5$pu.
b. Step-up voltage injection

A two winding transformer is connected as an autotransformer to boost the input voltage $U_p$ from 0.5pu to 1pu during voltage sag/swell. The voltage and current distribution in the autotransformer is shown in Fig. 7. It does not provide electrical isolation between primary side and secondary side but has advantages of high efficiency with small volume. The compensator considered is a shunt type as the control voltage developed is injected in shunt. The relationships of the autotransformer voltage and current are expressed as

$$\frac{U_L}{U_p} = a = \frac{I_s}{I_L} = \frac{N_1 + N_2}{N_2}$$  \hspace{1cm} (11)

where
- $U_p$ = Primary voltage
- $U_L$ = Secondary voltage = Load voltage
- $a$ = turns ratio,
- $I_1, I_2$ = Primary and secondary currents, respectively
- $I_s, I_L$ = Source and load currents, respectively
- $N_1, N_2$ = Number of turns in primary and secondary windings, respectively.

Fig. 7. Voltage and current relations in an autotransformer

A transformer with $N_1 : N_2 = 1:1$ ratio is used as an autotransformer to boost the voltage on the load side when sag is detected and can mitigate up to 50% voltage sag. This is also verified from Fig. 2 where a duty ratio of 1 (maximum value) is required for 50% voltage sag at the supply. As the turns ratio of the transformer equals 1:2 in autotransformer mode, the magnitude of the load current $I_L$ (high voltage side) is the same as that of the primary current $I_1$ (low voltage side). From (11), it is clear that $U_L = 2U_p$ and $I_s = 2I_L$. The voltage across the switch in the off-state is equal to the magnitude of the input voltage. When sag is detected by the voltage controller, IGBT is switched ON and is regulated by the PWM pulses. The primary voltage $U_p$ is such that the load voltage on the secondary of autotransformer is the desired rms voltage.

c. Ripple filter design

The output voltage $U_p$ is a pulsed voltage containing fundamental component of 50Hz and odd harmonics at switching frequency as given by (2). Simulation is performed for 30% voltage sag and with triangular wave carrier frequency of 1500 Hz in the control circuit. The duty ratio given by PI controller is $K = 0.715$ for fundamental of $U_p = 0.5$ pu. Fig. 8(a) shows voltage $U_p$ waveform with 15 pulses per half-cycle and Fig. 8(b) shows the harmonic spectrum of $U_p$ containing harmonics of order of integer multiple of carrier frequency.

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Fig. 8. Simulation results of ac voltage controller output voltage for 30% voltage sag and duty ratio $K = 0.715$. (a). Voltage $U_p$, and (b). Harmonic spectrum of $U_p$.

Simulation is performed for various percentages of voltage sag and harmonic spectrum of $U_p$ thus obtained is shown in Fig. 9(a). Maximum harmonics occur during the 10% of sag or $U_{sag} = 0.9$ pu as under this condition the duty ratio is 0.555 (Fig. 2). Here $U_{sag}$ represents the remaining voltage of $U_s$ during sag. For voltage sag of 50% magnitude, $K=1$ and harmonics are absent in $U_p$. Fig. 9(b) shows the plot of harmonic for disturbance swell varying from 10% to 80% (1.1 pu to 1.8 pu).

![Bar Chart](image)

Fig. 9. Magnitude of harmonics in $U_p$ without ripple filter for (a). various voltage sag conditions and (b). various voltage swell conditions

Ripple filter at the output of the controller is designed to maintain the load voltage THD within the limits. Ripple filter rating is determined by the harmonics at 10% sag as large amount of harmonics are present at this condition. A combination of low pass filter for the fundamental component and notch filter to remove the harmonics is used as shown in Fig. 2. The capacitor required for the filter is designed by considering its kVA to be 25% of the system kVA as

$$\frac{U_{\text{rms}}^2}{X_C} = 0.25 \times \frac{VA_{\text{sys}}}{S_{\text{rms}}}$$  \hspace{1cm} (12)

Capacitor value ($C_{total}$) thus obtained is divided into $C_{r1}$ and $C_{r2}$ equally. Capacitor $C_{r2}$ in
combination with source inductance and leakage inductance form the low pass filter. The notch filter is designed with a center frequency of PWM switching frequency by using a series LC filter as

$$f_{pwm} = \frac{1}{2\pi \sqrt{L_r C_{r1}}} \quad (13)$$

To limit the filter current a resistor may be added. The impedance of the filter is given by

$$|z| = \sqrt{R^2 + (\omega L_r - \frac{1}{\omega C_{r1}})^2} \quad (14)$$

where $R$, $L_r$, and $C_{r1}$ are the notch filter resistance, inductance and capacitances respectively. The notch filter designed for switching frequency resonance condition is capacitive in nature for frequencies less than its resonance frequency. Hence at fundamental frequency it is capacitive of value $C_{r1}$ and is in parallel with $C_{r2}$ resulting to $C_{\text{total}}$.

d. Snubber design

IGBT switch $SW$ operates only during voltage sag or swell condition and regulates the output voltage according to the PWM duty-cycle. RC snubber circuits are connected across the IGBT and thyristors to suppress the over voltages that occur when the switches are turned off. The design of RC snubber circuit is described in this section.

Snubber circuit with $R_{sb}$ and $C_{sb}$ is used for dv/dt protection of IGBT switch $SW$ and to provide path for current is shown in Fig. 10(a). The snubber circuit design is based on the system rating and thermal voltage specification of IGBT. Resistor $R_{sb}$ is used to dampen the energy transfer to the capacitor when the IGBT turns off and to limit the capacitor discharge current when the IGBT turns on. Based on datasheet specification of IGBT, snubber resistance $R_{sb}$ is calculated as

$$R_{sb} = \text{Peak repetitive voltage} / \text{Peak current} \quad (15)$$

The approximate capacitance value $C_{sb}$ of the snubber is determined by two conditions. The first condition is that the peak voltage during the IGBT off-state should be lower than peak repetitive voltage of IGBT, and the second condition is that the capacitor voltage needs to discharge to lower than 10% of its charged value during the IGBT turn-on. Second condition is satisfied when the minimum IGBT on-state time (obtained from its datasheet) is greater than $2.5 \times R_{sb} \times C_{sb}$. $R_{sb}$ and $C_{sb}$ are designed from the condition of restricting the initial discharge current and discharge time of the snubber circuit, respectively. The equivalent circuit of the system in Fig. 10(b) is the condition when IGBT switch $SW$ is off. $U_1$ and $U_2$ represent the transformer primary and secondary voltages, respectively and $L_s$ is the source inductance. VSSC acts only when sag is detected. Then the supply voltage $U_s$ is the sag voltage or the remaining voltage during sag given by $U_{sag} = U_n - U_{dp}$, where $U_n$ is the supply voltage under normal condition and $U_{dp}$ represents the drop in supply voltage. From Fig. 10(b) following expressions (16) and (17) are obtained.
Fig. 10(a). RC snubber connection to IGBT, (b). Equivalent circuit of the system when IGBT is off, and (c). Simplified equivalent circuit.

\[ u_s - u_L = u_{dp} = 2L_s \frac{di_L}{dt} - 2R_{sb}i_L - \frac{2}{C_{sn}} \int i_L \, dt \]  \hfill (16)

and

\[ u_s = u_n - u_{dp} = -2L_s \frac{di_L}{dt} + 2R_{sb}i_L + \frac{2}{C_{sb}} \int i_L \, dt \]  \hfill (17)

where \( R_1, R_2 \) = transformer leakage winding resistance, \( L_1, L_2 \) = transformer leakage winding inductance and \( U_{dp} \) represents the voltage magnitude supported by VSSC. With 1:1 two-winding transformer used as an autotransformer, \( U_1 = U_2, L_1 = L_2 \) and \( R_1 = R_2 \). Simplifying (16) and (17), we get
\[ u_n - 2u_{d_{ip}} = -4L_s \frac{di_L}{dt} + 4R_{ab} i_L + \frac{4}{C_{ab}} \int i_L \, dt \]
\[ + 2L_i \frac{di_L}{dt} + 2R_i i_L \]

Simplified equivalent circuit with load current \( i_L \) is shown in Fig. 10(c). Snubber voltage \( U_{ab} \) and hence capacitance \( C_{ab} \) is derived from Fig. 10(c).

4. SIMULATION ANALYSIS AND RESULTS

Simulation analysis is performed on a three-phase, 132/13.8 kV, 5 MVA, 50 Hz distribution system to evaluate the potential of the PWM switched autotransformer to compensate voltage sag and swell disturbances. PSCAD/EMTDC model of the system used for analysis is shown in Fig. 11.

![Fig. 11. PSCAD/EMTDC model of a 3-phase system used for voltage sag study](image)

<table>
<thead>
<tr>
<th>Table 1. System Parameters Used for Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation</td>
</tr>
<tr>
<td>Transformer</td>
</tr>
<tr>
<td>T2, T3: 12/13.8 kV, 1 MVA, 50 Hz</td>
</tr>
<tr>
<td>T4: 13.8 kV/400V, 5 kVA, 50 Hz</td>
</tr>
<tr>
<td>Autotransformer</td>
</tr>
<tr>
<td>Secondary: 230V, 5 kVA, 50 Hz</td>
</tr>
<tr>
<td>Ripple filter at output of</td>
</tr>
<tr>
<td>Autotransformer</td>
</tr>
<tr>
<td>PI controller gain</td>
</tr>
</tbody>
</table>

Simulation analysis was performed for two cases of voltage sags - sag due to fault and sag due to induction motor starting. Three kinds of loads R load, RL load and RC loads are considered as sensitive loads which are to be supplied at constant voltage. Voltage swell analysis is performed by considering capacitor switching. Table 1 shows the system parameter specifications used for simulation.

a. Voltage sag due to fault

Voltage sag is created at point F as shown in Fig. 12 during simulation by applying 3-
phase-to-ground fault through a fault resistance for a period of 0.4 sec (20 cycles) from $t_1 = 0.2$ sec to $t_2 = 0.6$ sec. Fig. 12(a) shows voltage at the sensitive load indicating a drop of 30\% in magnitude from 0.2 sec to 0.6 sec until the fault is cleared. The IGBT gate pulses from PWM generator shown in Fig. 12(b) are generated by comparing triangular waveform (carrier signal) with $U_{\text{control}}$ signal in Fig. 12(c). VSSC regulates the load voltage to attain its normal value in about 1 cycle shown in Fig. 12(d). Compensated and uncompensated rms voltages (pu) are shown in Fig. 12(e) showing that VSSC compensator maintains load voltage equal to the reference value. Load current and filter current are shown in Figs. 12(f) and (g) respectively.

Fig. 12(a). Voltage across sensitive load without mitigation device, (b). Gate pulses, (c). Control voltage generated by PI controller (d). Load voltage with VSSC on, (e). Rms load voltage for without and with mitigation device, (f). Load current Filter current, and (g). Compensated reactive power

A dip in voltage magnitude (rms) is observed at various buses as given in Table 2. Voltage at bus5 at which the sensitive load is connected is protected by PWM switched autotransformer and all other bus voltages are not affected by its operation.

<table>
<thead>
<tr>
<th>Mitigation Device</th>
<th>Voltage at bus1 (pu)</th>
<th>Voltage at bus2 (pu)</th>
<th>Voltage at bus3 (pu)</th>
<th>Voltage at bus4 (pu)</th>
<th>Voltage at bus5 (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>ON</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 3 summarizes the simulation results for mitigation of various percentages of sags when protecting a sensitive load taken as RL load of value 9 Ω and 0.2 H. The THD of the load voltage is within the limits (IEEE std. 519). With 1:1 autotransformer ratio, mitigation capability of the device is up to about 50% of sag. The effectiveness of the mitigation device is also tested by considering various sensitive loads (RL and RC loads) with 30% voltage sag. The results are tabulated in Table 4. In all the cases, the compensating could maintain the THD of the load voltage within the limits.

<table>
<thead>
<tr>
<th>Sag (%)</th>
<th>(U_L) (pu)</th>
<th>(U_L) THD (%)</th>
<th>(I_L) THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.18</td>
<td>0.9947</td>
<td>3.02</td>
<td>0.91</td>
</tr>
<tr>
<td>11.19</td>
<td>1.010</td>
<td>4.71</td>
<td>3.72</td>
</tr>
<tr>
<td>16.75</td>
<td>0.9982</td>
<td>2.80</td>
<td>1.43</td>
</tr>
<tr>
<td>20.10</td>
<td>1.0034</td>
<td>3.03</td>
<td>2.86</td>
</tr>
<tr>
<td>25.10</td>
<td>1.0083</td>
<td>2.24</td>
<td>1.36</td>
</tr>
<tr>
<td>33.40</td>
<td>0.9783</td>
<td>2.63</td>
<td>2.31</td>
</tr>
<tr>
<td>40.10</td>
<td>0.9686</td>
<td>2.10</td>
<td>0.93</td>
</tr>
<tr>
<td>47.10</td>
<td>0.90</td>
<td>1.93</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 4. THDs of compensated Load Voltage and Currents for Various Loads (for 30% Voltage sag)

<table>
<thead>
<tr>
<th>Load</th>
<th>(U_L) (pu)</th>
<th>(U_L) THD (%)</th>
<th>(I_L) THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Ω, 0.2 H</td>
<td>0.9794</td>
<td>2.1197</td>
<td>0.0805</td>
</tr>
<tr>
<td>5 Ω, 0.2 H</td>
<td>1.0054</td>
<td>2.3974</td>
<td>1.91</td>
</tr>
<tr>
<td>3 Ω, 0.2 H</td>
<td>1.0098</td>
<td>2.9400</td>
<td>1.31</td>
</tr>
<tr>
<td>1 Ω, 0.2 H</td>
<td>1.0150</td>
<td>2.7290</td>
<td>0.99</td>
</tr>
<tr>
<td>9 Ω, 0.2 H</td>
<td>0.9794</td>
<td>2.1197</td>
<td>0.0805</td>
</tr>
<tr>
<td>9 Ω, 0.15 H</td>
<td>0.9788</td>
<td>2.9846</td>
<td>1.4730</td>
</tr>
<tr>
<td>9 Ω, 0.1 H</td>
<td>0.9542</td>
<td>2.1193</td>
<td>0.9790</td>
</tr>
<tr>
<td>1 Ω, 1.0 μF</td>
<td>1.0029</td>
<td>0.10047</td>
<td>0.15388</td>
</tr>
<tr>
<td>1 Ω, 0.1 μF</td>
<td>0.97096</td>
<td>0.1243</td>
<td>0.19054</td>
</tr>
</tbody>
</table>

b. Voltage sag due to induction motor starting

Proposed method of mitigation is also tested with simulation for variable sag by considering induction motor starting. Industrial applications of induction motor are of large power rating used as adjustable speed drive, and traction motor. When an induction motor is started it draws large starting currents resulting into a steep dip in voltage followed by a gradual recovery. The recovery of the voltage to normal value takes several cycles. Such type of voltage disturbances occurring at high voltage bus may create voltage dip at the sensitive loads connected at low voltage bus. Simulation analysis is performed by considering two induction motors which are starting at same time and at different instants. In the first case, both the induction motors (IM1 and IM2) in Fig. 11 are started simultaneously at time \(t = 0.5\) sec.

Voltage sag of 40% magnitude is observed and instantaneous supply voltage is shown in Fig. 13(a). PWM switched autotransformer is switched ON by the control circuit to compensate this variable voltage sag. Fig. 13(b) shows the rms value of load voltage for
without and with compensator. Steady state is reached (nominal voltage) at $t = 1.3$ sec.

In the second case, induction motors are started at different instants. IM1 is started at $t = 0.5$ sec at which $20\%$ sag is observed and steady state is reached at $t = 0.925$ sec. Later IM2 is started at $t = 1.5$ sec which results to $20\%$ sag and voltage reaches steady state at $t = 2.0$ sec. Supply voltage waveform for this case of two separate events is shown in Fig. 13(c). The corresponding rms load voltage waveforms of both uncompensated and compensated conditions are shown in Fig. 13(d).

In the third case, the voltage events are overlapped such that IM1 is started first at $t = 0.5$ sec and before steady state is reached IM2 is started at $t = 0.8$ sec. Instantaneous supply waveform is shown in Fig. 13(e). When IM1 is started at $t = 0.5$ sec rms voltage is $0.8pu$. This voltage has reached to $0.88pu$ at $t = 0.8$ sec. Due to start of IM2 at $t = 0.8$ sec, rms voltage drops to $0.68$ pu. Percentage sag is $32\%$ and the corresponding rms load voltage waveforms of both uncompensated and compensated cases are shown in Fig. 13(f).

For all the above cases of induction motor starting, PWM switched autotransformer is capable of maintaining THDs of load voltage and currents well within the limits as per the standard (IEEE std. 519).

Fig. 13. Simulation study for induction motor starting (a). Supply voltage when two induction motors started simultaneously, (b). RMS voltage at the supply and compensated rms load voltage, (c). Supply voltage when two induction motors started at different intervals, (d). RMS voltage at the supply and compensated rms load voltage, (e). Supply voltage when IM2 is started before steady state reached due start of IM1, (f). RMS voltage at the supply and compensated rms load voltage.
c. Voltage swell due to capacitor switching

Capacitor switching is a common process at substations used for power factor improvement. Due to this there is an increase in leading VAR resulting in voltage magnitude rise. PWM switched autotransformer is tested for protection of sensitive load against this voltage swell. Fig. 14 (a) shows the instantaneous supply voltage waveform for capacitor switching operation at bus 1 with capacitor connected at t = 0.2 secs and disconnected at t = 0.6 secs. Peak detector circuit has given a voltage magnitude of 1.11 pu indicating 11% voltage swell. Fig. 14(b) shows the supply voltage rms which would be the uncompensated load voltage. When PWM switched autotransformer is connected in the system the load voltage was maintained to 1.02 pu.

Performance of the device is tested for various swell conditions by connecting capacitor at bus 1. Table 5 summarizes the load voltage for without and with PWM switched autotransformer in action. The new mitigation device is found effective in compensating both voltage sag and swell.

![Graph showing voltage swell compensation](image)

**Fig. 14.** Simulation results for voltage swell compensation. (a). Supply voltage and its peak value, and (b). RMS load voltage with and without compensator.

<table>
<thead>
<tr>
<th>Capacitor switching at bus1</th>
<th>$U_S$ (pu)</th>
<th>$U_L$ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Ω, 150 μF</td>
<td>1.11</td>
<td>1.02</td>
</tr>
<tr>
<td>10 Ω, 150 μF</td>
<td>1.14</td>
<td>1.02</td>
</tr>
<tr>
<td>5 Ω, 150 μF</td>
<td>1.16</td>
<td>1.01</td>
</tr>
<tr>
<td>5 Ω, 200 μF</td>
<td>1.20</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 5. Supply and Load Voltages during Swell Compensation

5. EXPERIMENTAL RESULTS

Prototype has been built for single phase 230 volts, 50 Hz system and tested for mitigation of voltage sag and swell. Fig. 15(a) depicts the arrangement of the practical system used for experimentation. Artificial transmission line system of length 750 km is supplied with 243volts at the sending end for which the receiving end voltage is 230volts with 1kVA resistive load and sensitive load connected. Receiving end voltage of 230 volts is taken as reference. Table 6 lists the specification of the system used for testing. Fig. 15(b) shows the arrangement of transmission line system, loads, and power circuit of VSSC.
Fig. 15. Experimental setup for sag and swell mitigation with PWM controlled step-up voltage injection.

Table 6. System Parameters for Experimental Setup

<table>
<thead>
<tr>
<th></th>
<th>Supply</th>
<th>1-phase, 230V, 50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Transformer</td>
<td>1-phase, 230V/230V, 50 Hz, 10 kVA</td>
</tr>
<tr>
<td>3</td>
<td>Transmission Line Parameters</td>
<td>750 kms, 4-pi sections, L = 0.1mH/km, C = 0.1 µF/km, Surge impedance = 31 ohms</td>
</tr>
<tr>
<td>4</td>
<td>Load</td>
<td>Resistive Load:  230V, 1kVA – 3No.s, 230V, 0.5kVA – 1No.s , 230V, 0.25kVA – 1No.s Sensitive Load: Resistive, 230V, 0.5 kVA</td>
</tr>
<tr>
<td>5</td>
<td>Ripple Filter</td>
<td>L=2.5mH, C1=C2=10uF, Q=15</td>
</tr>
<tr>
<td>6</td>
<td>Auto Transformer</td>
<td>1-phase, 230V, 1:1, 50 Hz, 1kVA</td>
</tr>
</tbody>
</table>
Fig. 16. Control circuit waveforms (a). $U_{\text{ref}}$ and $U_{\text{ref}}$, and (b) Gate pulses.

Fig. 17. Voltage waveforms at sensitive load for voltage sag of 5 cycles (a). without compensation and (b). with compensation

Under normal condition the power flow to the sensitive load is through the bypass switch. Peak detector unit continuously monitors the receiving end voltage. Voltage sag of 17.4% is observed by connecting an additional 0.5kVA load (switching on S3) and 26.1% of sag is produced when 1kVA load is switched on (switching on S1 or S2). When sag occurs due to connection of loads a logic signal is generated activating the control circuit. Fig. 15(c) shows the circuit for generation of gate pulses and gate driver circuit for connecting the gate pulses to IGBT switch.

A digital phosphor oscilloscope - Tektronix TDS 3032B, 300MHz, is used during experimentation. Fig. 16 shows the gate pulses obtained by comparing the triangle waveform $U_{\text{ref}}$ with the $U_{\text{ref}}$ for voltage with 26.1% sag. Fig. 17(a) shows the load voltage waveform without compensator. Fig. 217b) is the compensated $U_{l}$ obtained when VSSC is in action. The load voltage waveform is improved by using the ripple filter designed and compensated load voltage THD is 32% without ripple filter and 1.59% with filter satisfying the IEEE std. 519 specification. This validates the performance of VSSC designed for compensation of voltage sag.

6. CONCLUSIONS

This paper has presented the voltage sag/swell compensator as a mitigating device for compensating both voltage sag and swell. Detection of disturbance is very fast with peak voltage estimation and smooth compensation is obtained with control circuit based on time-ratio control. The proposed technique is simple, requires only one IGBT switch per phase and is economical compared to commonly used DVR or STATCOM. Simulation results are presented for mitigation of constant sag, variable sag and swell disturbances. Experimental results verify that the proposed device is efficient in compensating the voltage disturbances and load voltage THD is within the limits.
References


