Automatic Voltage Regulator Using an AC Voltage–Voltage Converter

Steven M. Hietpas, Member, IEEE, and Mark Naden, Student Member, IEEE

Abstract—Voltage sags and extended undervoltages are one of the main concerns of industry today. These voltage sags could cause high negative impact on productivity, which is certainly an undesirable aspect in industrial and commercial applications. Current tap-changing transformers used in distribution systems have proven to be inadequate in solving these problems related to line regulation. A solution to these problems is to install an ac voltage–voltage converter that has been developed primarily for voltage-sag correction. This system incorporates high-speed insulated gate bipolar transistor switching technology and was designed to provide the speed and efficiency required by industrial customers. Furthermore, the system will provide the flexibility of installation with or without the incorporation of tap-changing transformers. Simulation results show the operations involved in voltage-sag correction of the ac voltage–voltage converter. A single-phase system can be readily developed into a three-phase converter system based on the exact principle of operation.

Index Terms—AC–AC buck, ac voltage–voltage converter, insulated gate bipolar transistors, power quality, tap-changing transformers, voltage sags.

I. INTRODUCTION

P
er quality describes the quality of voltage and current of a facility has, and is one of the most important considerations in industrial and commercial applications today. It is essential that processes, in particular, in industrial plants, operate uninterrupted where high productivity levels are an important factor. Power quality problems commonly faced by industrial operations include transients, sags, swells, surges, outages, harmonics, and impulses that vary in quantity or magnitude of the voltage. Of these, voltage sags and extended undervoltages have the largest negative impact on industrial productivity, and could be the most important type of power quality variation for many industrial and commercial customers.

Voltage sags are momentary voltage variations, usually caused by a short circuit or fault somewhere in a power distribution system, as shown in Fig. 1.

Recent survey results show that a typical distribution system customer experiences an average of 70 events per year where the voltage drops below 70% of the nominal. Interruptions of a few cycles could affect complex processes that use precision electronic equipment and computerized control. The Computer and Business Equipment Manufacturers Association (CBEMA) also found that sags below 70% are likely to impact data processing equipment.

Some major problems associated with unregulated line voltages (in particular, long-term voltage sags) include equipment tripping, stalling, overheating, and complete process shutdowns. These subsequently lead to lower efficiencies, higher power demand, higher cost for power, electromagnetic interference to control circuits, excessive heating of cables and equipment, and increased risk of equipment damage. The need for line voltage regulation still remains a necessity to meet demands for high industrial productivity.

There are several conditioning solutions to voltage regulation, which are currently available in the marketplace. Among the most common are tap-changing transformers, which are the types of voltage regulators used in today’s power distribution systems. However, these methods have significant shortcomings. For instance, the tap-changing transformer requires a large number of thyristors, which results in highly complex operation for fast response. Furthermore, it has very poor transient voltage rejection, and only has an average response time.

Some solutions have been suggested to encounter the effects of voltage sag in [7], [9], and [10], but have not been developed fully towards replacement of tap-changing transformers. An ac voltage–voltage converter prototype is under development at South Dakota State University, Brookings, to provide solutions to problems related to line regulation, which will meet the power quality preferred by industrial customers.

The remainder of this paper is divided into three major sections. Section II provides details of the design and description of the ac voltage–voltage converter model. Section III contains simulation results showing the functionality of the design. Section IV illustrates several options that incorporate the converter into tap-changing transformer configurations, as well as for complete replacement. The paper ends with concluding remarks.

II. AC VOLTAGE–VOLTAGE CONVERTER MODEL

The ac voltage–voltage converter model is based on a buck converter (\( V_{\text{in}} \leq V_{\text{out}} \)) configuration, with a step-up injection transformer used at its output. The converter incorporates fast-switching insulated gate bipolar transistor (IGBT) technology, and controls involving pulsewidth modulation (PWM) techniques. The model block diagram is shown in Fig. 2.

Letting \( V_{\text{nom}} \) (Fig. 2) represent the nominal line voltage, a voltage sag is present when \( V_s \) (the true line voltage) is less than
Fig. 1. Typical voltage sag.

The objective is to regulate $V_{\text{out}}$ to $V_{\text{nom}}$ when a voltage sag is present. In Fig. 2, the converter output voltage, $V_{\text{pri}}$, is determined by the duty cycle $D$ based on negative feedback of the output line voltage. The value for $D$ is given by

$$D = \frac{V_{\text{pri}}}{V_S}. \tag{1}$$

Through closed-loop feedback, the duty cycle changes according to the degree of source voltage drop (sag). The output voltage of the converter $V_{\text{pri}}$ is injected in series with the line through the injection transformer, where the turns ratio $\alpha$ is given by

$$\alpha = \frac{V_{\text{pri}}}{V_{\text{sec}}}. \tag{2}$$

Let the output voltage $V_{\text{out}}$ represent the line-to-line voltage on the load side of the injection transformer. Assuming negligible phase shift from $V_{\text{pri}}$ to $V_{\text{sec}}$, as well as negligible phase shift from $V_S$ to $V_{\text{pri}}$, the magnitude of this output line voltage is $V_{\text{out}} = (V_S + V_{\text{sec}})$ and can further be simplified to

$$V_{\text{out}} = V_S \left(1 + \frac{D}{\alpha}\right). \tag{3}$$

We define the percentage voltage sag as

$$P_{\text{seg}} = 100(1 - \frac{V_S}{V_{\text{nom}}}). \tag{4}$$

The required turns ratio $\alpha$ is based on the worst case $P_{\text{seg}}$ anticipated. Under worst case conditions (maximum $P_{\text{seg}}$), noting that the objective is to regulate $V_{\text{out}}$ to $V_{\text{nom}}$, and using (1)–(4), two design equations result and are given in (5) and (6). The design equation for $\alpha$ is given by

$$\alpha = \frac{(100 - P_{\text{seg}})}{P_{\text{seg}}} \tag{5}$$

and for a given transformer turns ratio $\alpha$, the duty cycle for a regulated output is given by

$$D = \frac{(V_{\text{nom}} - V_S)}{(V_S/\alpha)}. \tag{6}$$

$D$ is a function of the PWM signal, which is essentially a square wave with a variable pulse width (shown in Fig. 3). Based on Fig. 3, $D$ is given by

$$D = \frac{t_{\text{on}}}{T}. \tag{7}$$

where $t_{\text{on}}$ is the time that switches $X1$ and $X2$ are on in a given switching period, $T$. The complementary pair $Y1$ and $Y2$ are on for the remaining period of time, $t_{\text{off}}$ (see Fig. 10).

Table I shows the required value of transformer turns ratio $\alpha$ for a range of expected worst case voltage sags.

![Fig. 3. Square-wave PWM signal.](image)

![Fig. 4. Turns ratio $\alpha$ as a function of $P_{\text{seg}}$.](image)

![Table I](image)

<table>
<thead>
<tr>
<th>$P_{\text{seg}}$ (%)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>85</th>
<th>95</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>3</td>
<td>1</td>
<td>1/3</td>
<td>1/5.67</td>
<td>1/19</td>
</tr>
</tbody>
</table>

Table II shows the various values of $D$ for a range of voltage sags, assuming a worst case voltage sag of 75%, hence, the requirement for a 1:3 step-up transformer ($\alpha = 1/3$).

Fig. 4 shows a plot for $\alpha$ versus $P_{\text{seg}}$ based on (5). Fig. 5 is a schematic of a single-phase ac voltage–voltage converter.

Table II shows various plots for $D$ as a function of $P_{\text{seg}}$ for a range of specified worst case sag conditions and transformer turns ratios.

**III. SIMULATION RESULTS AND ANALYSIS**

SPICE simulation results demonstrate the operation of the converter model. Simulation results use ideal characteristics of circuit components.

The design example considered is based on the assumption that the distribution system may experience as much as 75% voltage sag due to certain disturbances. Fig. 7 shows how the converter corrects a voltage sag of 60% from the nominal line.
TABLE II

VALUES OF $D$ FOR A RANGE OF VOLTAGE SAGS ASSUMING A WORST CASE SAG OF 75%

<table>
<thead>
<tr>
<th>% Sag</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>60</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.0</td>
<td>0.11</td>
<td>0.33</td>
<td>0.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Max $P_{\text{avg}} = 25.50.75.85.95$

$a = 3 \quad 1 \quad 1/3 \quad 1/5.7 \quad 1/19$

Fig. 6. $D$ as a function of $P_{\text{avg}}$ for a range of expected worst case voltage sags and selected transformer turns ratio.

Fig. 7. Ideal characteristics of the voltage-sag correction, where $V(\text{RL:2})$ is the output line voltage and $V(VL:+)$ is the input line voltage.

Fig. 8 (curve from Fig. 6 where $[\text{Max } P_{\text{avg}}, a] = [75, 1/3]$) shows the steady-state duty cycle $D_{\text{sag}}$ that is required for voltage-sag correction under these specified conditions. Changes in the duty cycle only take place half a cycle after the sag occurs, as this is the minimum time required to sense and
convert the ac voltage into an rms value. The duty cycle can be changed either instantly after the half-cycle rms calculation, or ramped up for the same period of time over the remaining half cycle (less transient disturbance effect). As the duty cycle is adjusted, the converter output voltage is boosted by the series injection transformer and added to the line voltage. This process yields a regulated output voltage $V_{out} = 208 \, V_{RMS}$.

Fig. 9 shows the converter output voltage based on the voltage sag conditions shown in Fig. 7. Small transients are observed due to the instantaneous change of the duty cycle. Fig. 10 shows the ripple on the output voltage and how it increases during the voltage sag or fault condition.

Further discussion on these issues concerning the ripple content and mathematical expressions used for the calculation of component values involved are available in Fig. 10.

IV. APPLICATION OF THE AC VOLTAGE–VOLTAGE CONVERTER

The ac voltage–voltage converter was designed to provide great flexibility to the industrial customer in choosing the method of installation that will apply in voltage regulation for a power distribution system. Some options have been studied based on various facts about how feasibly this model will fit in a distribution system, with or without the use of tap-changing transformers. Three possible options are briefly described below.

A. Option 1—Combined Tap-Changing Transformer and Converter

In order to achieve a well-regulated voltage, the ac voltage–voltage converter is coupled in series at the output of the tap transformer, as shown Fig. 11.

In this case, the converter will be continuously switching, i.e., converting voltage, constantly monitoring the tap transformer output voltage, and regulating the line voltage to the load. When a voltage sag occurs at any instance, the tap-changing transformer automatically selects a tap that would provide a voltage closest to the nominal (usually ±3% [7]). If a tap transformer with fewer tap settings is in place, with correspondingly less than adequate regulation, the regulation can be greatly enhanced with the converter in series with its output. Not only is the regulation significantly enhanced, but also the response time. Assuming the tap-changing transformer has its own local feedback, it will slowly increase its output while the duty cycle of the converter decreases in value. The primary advantage to retaining the tapped transformer is that, during steady-state operation, the voltage converter enters close to a quiescent state,
resulting in more acceptable efficiencies. A disadvantage is continued maintenance of the tapped transformer. Another disadvantage is simply the increased complexity of the system.

B. Option 2—Combined Tap-Changing Transformer and Converter with Ability to Disconnect Converter

When the converter enters a quiescent state as described in Option 1, the duty cycle of the converter approaches 0, depending on the regulation capability of the tapped transformer as well as that of the converter itself. If regulation is a secondary requirement to response time, yet the response time is still required to be greater than the tapped transformer, a switch can be placed in parallel across the secondary side of the injection transformer, as shown in Fig. 12.

The switch can be comprised of appropriate power semiconductors, such as the gate-turn-off thyristor. When a voltage sag is detected, the switch $S_1$ is closed at the next line zero-current crossing. Once $S_1$ is opened, the converter’s duty cycle $D$ is increased from a value of 0.0 to the necessary value to restore line regulation, with slightly slower response compared to Option 1.

Once regulation is achieved and the voltage sag does not exist, $S_1$ can be closed on the next zero-voltage crossing of the injection transformer’s output. Since the converter is essentially taken out of the regulation loop when $S_1$ is closed, regulation is only as good as the rating of the tapped transformer. A primary advantage of this option compared to Option 1 is improved efficiency, reduced maintenance and increased life expectancy of the converter. If the response time specification can be further relaxed, $S_1$ can be of mechanical variety with resulting increase in system efficiency. This approach is not recommended if response time does not surpass that of the tapped transformer alone. The complexity of this option is slightly greater than Option 1.

C. Option 3—AC Voltage Converter Without Tap-Changing Transformer

The third option replaces the tap-changing transformer with the ac voltage-voltage converter, as shown in Fig. 13. The converter is continuously in operation unless a similar switch as discussed in Option 2 is employed. This method of application eliminates the need for maintenance on tap changing transformers, and subsequently reduces maintenance and operating costs associated with Options 1 and 2.

The efficiency of the system could possibly be less than in Options 1 and 2, since the converter is processing power continuously. The actual values of efficiency are highly dependent on the design of the converter and can likely be optimized for a particular system. The response time of this configuration is equal to that of Option 1 and better than Option 2. Overall regulation is equal to or better than either Options 1 and 2. Complexity of design is also improved.

A single-phase system is currently being developed and can readily be made into a three-phase system by either combining three single-phase units or using a three-phase design shown in...
Fig. 14. Using three single-phase units provides the advantage of independent line regulation, but results in a higher cost (more IGBT’s required).

V. CONCLUSIONS

The simulation results provided in this paper have illustrated the feasibility of the ac voltage–voltage converter for voltage-sag correction. The efficiency and flexibility of using such a system in power distribution stations were discussed, and have been shown to provide a workable solution to current power quality problems. Three options discussed provide greater flexibility in voltage regulation systems at distribution substations and ensure adequate efficiency and power quality. Future work will include the hardware design and implementation of the system, including closed-loop feedback control necessary to achieve response and regulation requirements.

REFERENCES


Steven M. Hietpas (S’83–M’84) received the B.S. degree in electrical engineering and the M.S. and Ph.D. degrees from Montana State University, Bozeman, in 1984, 1991, and 1994, respectively. From 1984 to 1989, he was with the Space Energy Group, Space Systems Division, General Dynamics, San Diego, CA, where he worked on research and development of power processing/power electronics for the Shuttle Centaur Program and the International Space Station Program. He has been a member of the faculty at South Dakota State University, Brookings, since 1994 and currently holds the position of Associate Professor and also serves as the Coordinator for the Center for Power System Studies. His research interests include power electronics, power quality, and control.

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