A Novel Low Cost Three Arm Ac Automatic Voltage Regulator

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ABSTRACT
In this paper, a novel ac automatic voltage regulator (AVR) is proposed. This AVR is configured by an input inductor, an output filter, a small-capacitance dc capacitor, and a three-arm power converter. This three-arm power converter acts as an ac boost converter when the utility voltage is lower than the specified voltage. On the contrary, this three-arm power converter acts as an ac buck converter when the utility voltage is higher than the specified voltage. Hence, the output voltage of the AVR can be maintained at the specified voltage. The salient feature of this AVR is that the power electronic switches of only one arm are switched in high frequency, while those of the other arms are switched in low frequency. Hence, the switching loss of this AVR can be reduced. Moreover, the capacitance of the dc capacitor in the three-arm power converter is very small. Hence, the size and cost can be reduced, while the reliability and power efficiency can be increased. A prototype is developed and tested to verify the performance of the proposed AVR. The experimental results verify that the proposed AVR has the desired performance.

KEYWORDS: AC boost converter, ac buck converter, automatic voltage regulator (AVR).

INTRODUCTION

Computer-Related precision equipment has been widely used in many fields, and it requires a high-quality power source in maintaining normal operation. Voltage regulation is an important issue in the field of power quality improvement. Conventionally, a tap-changer autotransformer is a popular solution to the problems of under- and over-voltages. The tap-changer autotransformer connects the utility and a load, and it provides the load with a stable voltage by adjusting the tap of the transformer. However, voltage regulation of the tap-changer autotransformer has some disadvantages including step regulation of the supply voltage, large installation volume, and inability to improve the voltage distortion.

The dynamic voltage regulator has been reported to re-duce the installation size of automatic voltage regulator (AVR). However, it can only overcome the problem of under-voltage (voltage sag) but not that of over-voltage.

In recent years, AVRs implemented by a three-arm power converter have been reported. The conventional three-arm AVRs are shown in Fig. 1. Fig. 1(a) shows a double-conversion three-arm AVR. A battery set is often placed at the capacitor is dependent on the power rating of the load and the allowable ripple voltage of the dc bus, and it is generally several thousands of microfarads. In the double-conversion three-arm AVR, the entire power demanded by the load must be converted twice (ac to dc and dc to ac), and the power electronic switches of two or three arms in a three-arm power converter are switched in high switching frequency. Thus, it results in poor power efficiency. Moreover, a dc capacitor of several thousands of microfarads is required to act as an
energy buffer and sustain a constant voltage for normal operation of the three-arm AVR. Fig. 1(b) shows a transformer-coupled three-arm AVR [16]. This three-arm power converter is operated as a shunt converter configured by the first and second arms and as a series converter configured by the second and third arms. A large dc capacitor is still required at the dc bus of the power converter. The series converter is coupled between the utility and the load, and it will generate a voltage opposite to the variation in utility voltage so as to obtain a constant ac voltage for the load. The function of this coupling transformer is employed to match the voltage level. The shunt converter is connected to the utility in parallel to absorb or generate a real power demanded by the series converter for voltage regulation, thus sustaining the dc voltage of the power converter at a preset value. In comparison with the double-conversion three-arm AVR, the series and shunt converters in the transformer-coupled three-arm AVR process only a part of the power demanded by the load. The power electronic switches of two or three arms in the three-arm power converter are switched in high switching frequency at the same time. However, a large-size low-frequency transformer and a large dc capacitor are required in this AVR. To avoid using a low-frequency transformer, Fig. 1(c) shows the direct-coupled three-arm AVR [17], [18]. The three-arm power converter of this AVR is still operated as a shunt converter configured by the first and second arms and as a series converter configured by the second and third arms. Except that the series converter is directly connected to the load in series, the operation principle of the direct-coupled three-arm AVR is similar to that of the transformer-coupled three-arm AVR. However, a large dc capacitor still exists in the direct-coupled three-arm AVR.

This paper proposes a novel three-arm AVR. The proposed three-arm AVR acts as an ac boost converter when the utility voltage is lower than the specified voltage, and it acts as an ac buck converter when the utility
The voltage is higher than the specified voltage. Hence, the output voltage of the AVR can be maintained at the specified voltage. The power demanded by the load is directly supplied by the conversion results of the power converter (ac to ac). In comparison with the conventional three-arm power converter which requires double conversion (ac to dc and dc to ac), the proposed three-arm AVR requires only a single conversion. Moreover, the power electronic switches in only one arm of the three-arm power converter are switched in high frequency, while those of the other arms are switched in low frequency. The switching power loss is reduced, and no transformer.

**Fig. 2:** Circuit configuration of the proposed three-arm AVR.

Consequently, the proposed three-arm AVR has the advantages of reduced installation cost and volume, as well as increased reliability and power efficiency. To verify the performance of the proposed three-arm AVR, a prototype is developed and tested.

**System Configuration and Operation Theory:**

The circuit configuration of the proposed three-arm AVR is shown in Fig. 2. This AVR comprises a three-arm power converter, an input inductor, a small dc capacitor, and an output filter. The three-arm power converter of the proposed AVR acts as an ac boost converter when the utility voltage is lower than the specified voltage, and it acts as an ac buck converter when the utility voltage is higher than the specified voltage. Hence, the output voltage of the AVR can be maintained at the specified voltage. Since the power converter operates as an ac boost converter or an ac buck converter, the dc bus voltage of the power converter is a rectified utility voltage where the amplitude can be controlled. The dc bus voltage of the proposed three-arm AVR with a full-wave rectified voltage is different from that of the conventional three-arm AVRs with a constant dc voltage. Hence, there is no need to use a large dc capacitor of several thousands of microfarads in sustaining a constant dc voltage, and only a small dc capacitor of several tens of microfarads is applied to act as a snubber and filter circuit.

**A. AC Boost Mode:**

When the utility voltage is lower than the specified load voltage, the three-arm power converter operates as an ac boost converter. In this situation, the first and third arms are controlled by a square signal with the fundamental frequency of utility, and the second arm is controlled by a high-frequency pulse width modulation (PWM) signal. The operating circuit of the proposed AVR under the ac boost 1.
Fig. 3: Operating circuit of the proposed AVR under the ac boost mode. (a) Positive half-cycle. (b) Negative half-cycle.

Fig. 4: Related control signals of the power electronic switches and voltage waveforms of the proposed AVR under the ac boost mode.

off. When $G_3$ is on and $G_4$ is off, the inductor $L_A$ is energized through the utility, $G_1$ and $G_3$. In this duration, the inductor voltage ($v_{LA}$) is given by

$$v_{LA} = v_i$$  \hspace{1cm} (1)$$

where $v_i$ is the utility voltage. The current of the inductor $L_A$ is increased. The energy stored in the inductor $L_A$ will be released through $G_1$ and $G_2$ to the dc capacitor of the three-arm power converter when $G_3$ is off and $G_4$ is on, and the inductor voltage becomes

$$v_{LA} = v_d - v_c$$  \hspace{1cm} (2)$$

where $v_d$ is the dc bus voltage of the three-arm power converter. Since the dc bus voltage of the three-arm power converter will be higher than the utility voltage under the ac boost mode, the current passing through the inductor $L_A$ is decreased. When the current passing through the inductor $L_A$ is continuous, by applying Faraday’s law, the voltage-second balance can be represented as

$$v_i DT + (v_d - v_c)(1 - D)T = 0$$  \hspace{1cm} (3)$$
where $D$ and $T$ are the duty ratio and the switching period of $G_3$, respectively. From (3), the amplifier gain can be derived as

$$M_a = \frac{V_3}{V_o} = \frac{1}{1 - D}. \quad (4)$$

The operation of the three-arm power converter is similar to the dc/dc boost converter during the positive half-cycle. Fig. 3(b) shows the operating circuit while the utility voltage is in the negative half-cycle. As shown in Fig. 3(b), $G_1$ and $G_2$ are always on, and $G_3$ and $G_6$ are always off. The inductor $L_A$ is energized from the utility through $G_1$ and $G_2$ when $G_4$ is on and $G_3$ is off, and the energy stored in the inductor $L_A$ will be released to the dc capacitor of the three-arm power converter through $G_2$ and $G_1$ when $G_5$ is off and $G_4$ is on. The operation of the three-arm power converter is also similar to that of the dc/dc boost converter under the negative half-cycle, and the amplifier gain is also the same as (4). As shown in (4), the dc bus voltage of the three-arm power converter is a rectified ac voltage which is higher than the utility voltage when serving as an ac boost converter, and the amplifier gain is determined by the duty ratio $D$. The dc bus voltage of the three-arm power converter is inverted by the third arm, and then, it passes through the output filter so as to supply a load voltage higher than the utility voltage. Hence, the proposed AVR can sustain the load voltage at the specified voltage under the sag of the utility voltage. Fig. 4 shows the related control signals of the power electronic switches and the voltage waveforms of the dc/dc boost converter is dependent on the duty ratio [19]. Hence, the efficiency of the proposed AVR is also dependent on the amplifier gain shown in (4). The higher the amplifier gain is, the lower the efficiency of the proposed AVR will be. Since the voltage across the inductor $L_A$ is smaller than that of $L_A$ in the proposed AVR can be reduced. The ripple of the input current can be derived as

$$i_{L_A} = \frac{V_o D}{L_A f} \quad (5)$$

Where $f$ is the switching frequency. As shown in (5), the ripple of the input current is dependent on the duty ratio, switching frequency $f$, and inductor $L_A$. In the continuous conduction mode, the minimum product of $L_A$ and $f$ can be derived as

$$(L_A f)_{min} = D(1 - D)^2/2Z. \quad (6)$$

Where $Z$ is the load. Hence, the inductor $L_A$ can be determined by the switching frequency, specified ripple current, range of the duty ratio, and load. As shown in Fig. 3, the dc capacitor $C_A$ and output filter ($L_B$, $C_B$) form as a third-order low-pass filter to filter out the switching harmonic in the output voltage. Hence, a lower capacitance dc capacitor $C_A$ of several tens of microfarads can be selected.

**B. AC Buck Mode:**

When the utility voltage is higher than the specified load voltage, the three-arm power converter operates as an ac buck converter. In this situation, the first and second arms are controlled by a square signal with the fundamental frequency of utility, and the third arm is controlled by a high-frequency PWM signal. The inductor $L_B$ serves as the energy storage element when the three-arm power converter operates as an ac buck converter. Fig. 5(a) shows the operating circuit of the ac buck converter when the utility voltage is in the positive half-cycle. As shown in Fig. 5(a), $G_1$ and $G_2$ are always on, while $G_3$ and $G_4$ are always off. The utility voltage is rectified through the first and second arms of the three-arm power converter; thus, a rectified utility voltage appears at the dc bus of the three-arm power converter. Both the input inductor $L_A$ and the dc capacitor $C_A$ can perform as a low-pass filter. When $G_3$ is on and $G_6$ is off, the inductor $L_B$ is energized from the rectified utility voltage through $G_4$ and $G_5$. In this duration, the inductor voltage ($v_{L_B}$) can be represented as

$$v_{L_B} = v_C - v_o \quad (7)$$

Where $v_o$ is the load voltage. Since the rectified utility voltage is higher than the load voltage, the current passing through the inductor $L_B$ will be increased, and it stores energy in this duration. The energy stored in the inductor $L_B$ will be released to the load through $G_4$ and $G_6$ when $G_5$ is off and $G_6$ is on,

$$v_{L_B} = -v_o. \quad (8)$$

Hence, the current passing through the inductor $L_B$ will be decreased. When the current passing through the inductor $L_B$ is continuous and the Faraday’s law for the inductor $L_B$ is used, the voltage-second balance can be represented as

$$(v_C - v_o)DT + (v_C)(1 - D)T = 0 \quad (9)$$

Where $D$ and $T$ are the duty ratio and switching period of $G_6$, respectively. From (9), the dropped gain can be derived as

$$M_a = \frac{v_o}{v_C} = D. \quad (10)$$
Fig. 5: Operating circuit of the proposed AVR under the ac buck mode. (a) Positive half-cycle. (b) Negative half-cycle.

Since the input inductor $L_A$ and the dc capacitor $C_A$ form a low-pass filter, the rectified voltage of the three-arm power converter is close to the absolute utility voltage. Hence, the operation of the three-arm power converter is similar to the dc/dc buck converter under the positive half-cycle. Fig. 5(b) shows the operating circuit when the utility voltage is in the negative half-cycle. As shown in Fig. 5(b), $G_2$ and $G_3$ are always on, while $G_1$ and $G_4$ are always off. The utility voltage is rectified through the first and second arms of the three-arm power converter; thus, the dc bus voltage of the three-arm power converter is the negative utility voltage. The inductor $L_B$ is energized by the rectified utility voltage through $G_3$ and $G_6$ when $G_5$ is off and $G_6$ is on, and the energy stored in the inductor $L_B$ will be released to the load through $G_3$ and $G_5$ when $G_5$ is on and $G_6$ is off. The operation of the three-arm power converter is also similar to the dc/dc buck converter under the negative half-cycle, and the dropped gain is the same.

Fig. 6: Related control signals of the power electronic switches and voltage waveforms of the proposed AVR under the ac buck mode.

The dc bus voltage of the three-arm power converter. The dc bus voltage of the three-arm power converter is close to the absolute utility voltage. Hence, the relationship between the utility voltage and the load voltage is
close to (10) when serving as an ac buck converter. The dropped gain is determined by the duty ratio \(D\). Hence, the proposed AVR can sustain the load voltage at a specified voltage under the swell utility voltage. Fig. 6 shows the related control signals of the power electronic switches and voltage waveforms of the proposed AVR under the ac buck mode. Since the voltage across the inductor \(L_A\) is smaller than that of the conventional three-arm AVR, the inductance of the inductor \(L_B\) in the proposed AVR can be reduced. The ripple of the input current can be derived as

\[
 i_{LA} = \frac{(v_c - v_o)D}{L_Bf}.
\]

In the continuous conduction mode, the minimum product of \(L_B\) and \(f\) can be derived as the dc capacitor \(C_A\) form a low-pass filter to filter out the switching harmonic in the input current.

\[
 (L_B f)_\text{min} = (1 - D)Z/2.
\]

Fig. 7: Control block of the proposed three-arm power converter.

The amplifier gain \(M_v\) shown in (4) and (10) is derived from the continuous conduction mode of the inductor current. If the inductor current is discontinuous, the duty ratio must be decreased slightly in obtaining the same amplifier gain [19]. However, this problem can be solved effectively by a close-loop control of the output voltage. The output voltage will deviate from its desired value when the inductor current is discontinuous, and the controller of the output voltage can correct the duty ratio to trace the desired value. As discussed earlier, the conventional three-arm AVR utilizes a high-capacitance dc capacitor to provide a constant dc voltage, and at least four powers electronic switches of the conventional AVR are switched in high frequency. In accordance with the proposed AVR, either the second or the third arm is controlled via high-frequency switching. As a result, the power electronic switches of only one arm are switched in high frequency, while those of the other arms are switched in the fundamental frequency of the utility voltage. Hence, the switching loss can be reduced effectively. Moreover, the high-capacitance dc capacitor and high-inductance inductors employed in the conventional three-arm AVR are replaced by a small-capacitance dc capacitor and small-inductance inductors in the proposed AVR. The present design achieves lower cost and smaller volume for installation as well as lower switching loss.

Control Block Diagram:

Fig. 7 shows the control block diagram of the proposed AVR. It includes a utility voltage processing unit, a load voltage processing unit, and a selecting unit. The utility voltage is detected by a voltage detector, and then, it is sent to a zero-crossing detector. The output of the zero-crossing detector and its inverted signal are square waves in synchronization with the utility voltage. The capacitor \(C_A\) can be determined for a specified output to obtain the driving signals of \(G_1\) and \(G_2\) of the first arm. Ripple voltage. As shown in Fig. 5, the input inductor \(L_A\) and The detected utility voltage is also sent to a selecting circuit to high-frequency PWM signal \(S\) is selected to be the output of multiplexer II. Hence, the second arm is operated in low frequency, and the third arm is operated in high frequency so that the three-arm power converter is operated at the ac buck mode.

\[
 v_o = v_o(1 - D)\frac{8L_B}{C_Bf}.
\]

Simulation Results:

In order to verify the performance of the proposed AVR, a prototype is developed and tested. The controller of the prototype is implemented by a digital signal processor chip (TMS320F2407). Table I shows the main parameters of the proposed AVR. The capacitance of the dc capacitor \(C_A\) is only 20 \(\mu\)F, it is very small in comparison with that of the dc capacitor used in the conventional three-arm AVR [8]–[18].

Fig. 8 shows the experimental results of the proposed AVR under the utility voltage of 143 V and a resistive...
load. As shown in Fig. 8(c), the load voltage is close to sinusoidal and is regulated at 110 V. Fig. 9 shows the experimental results of the proposed AVR under the utility voltage of 77 V and a resistive load. As shown in Fig. 9(c), the load voltage is still almost sinusoidal and is regulated at 110 V. Fig. 10 shows the experimental results of the proposed AVR under the utility voltage of 121 V and nonlinear load. As shown in Fig. 10(d), the load current is distorted. However, the load voltage shown in Fig. 10(c) is still almost sinusoidal and is regulated at 110 V. Fig. 11 shows the experimental results of the output voltage for the proposed AVR upon varying the utility voltage from 77 to 143 V. It can be found that the output voltage varied between 113 and 108.9 V upon varying the utility voltage from 77 to 1.

**Fig. 8: Simulation Diagram.**

**Table 1:**

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>OUTPUT POWER</th>
<th>THD (V_util)</th>
<th>THD (V_load)</th>
<th>LOAD VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXISTING (R LOAD)</td>
<td>1 kW (approx)</td>
<td>0.0003</td>
<td>0.2621</td>
<td>110V</td>
</tr>
<tr>
<td>RL LOAD</td>
<td>832 W</td>
<td>0.0003</td>
<td>0.2621</td>
<td>110V</td>
</tr>
<tr>
<td>LOW COST AVR</td>
<td>2kW (approx)</td>
<td>0.2499</td>
<td>0.2621</td>
<td>230V</td>
</tr>
</tbody>
</table>

This means that the voltage regulation performance of the proposed AVR is very good. The experimental results of the total harmonic distortion (THD) for the proposed AVR upon varying the utility voltage from 77 to 143 V. The load is a resistive load of 1 kW. The THD of the utility voltage is about 4%, and the THD of the load voltage is still smaller than that of the utility voltage. The experimental results of the proposed AVR upon changing the utility voltage abruptly from 143 to 77 V. The output voltage maintains at the specified load voltage regardless of the variation in utility voltage. Since the load is constant, the variation in the utility current is inversely proportional to the variation of the utility voltage. The experimental results of the proposed AVR upon varying the utility voltage abruptly from 77 to 143 V.

**Conclusion:**

A novel AVR configured by a three-arm power converter has been proposed in this paper. The proposed AVR is operated as an ac boost under over-voltage of the utility, and it is operated as an ac buck when the utility is under-voltage. The salient feature of this AVR is that the power electronic switches of only one arm are switched in high frequency, while those of the other arms are switched in low frequency. Hence, the switching loss of this AVR is reduced. Since the voltage across the inductor is smaller than that of the conventional three-arm AVR, the inductance applied in the proposed AVR can be reduced. Moreover, there is no need to use a large dc capacitor in sustaining a constant dc voltage. Hence, the size can be decreased, the cost can be reduced, and the life of the power converter can be extended. A prototype is developed and tested to verify the
performance of this AVR. The experimental results verify that the performance of the proposed AVR is as expected.

Fig. 9: Experimental results of the proposed AVR for Boost Mode (a) Utility voltage. (b) Utility load (c) Pout (W) (d) Speed (rad/s)

Fig. 10: Experimental results of the proposed AVR for Buck Mode (a) Utility voltage. (b) Utility load (c) Pout (W) (d) Speed (rad/s).

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