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Performance of Three-Arm Ac Automatic Voltage Regulator

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ABSTRACT
In this paper the design and simulation of automatic voltage regulator (AVR) is proposed. The AVR provides voltage buck and boost capability to eliminate power problems created by under voltage or over voltage fluctuations. It also protects against minor and severe spikes and surges that comprise over 80% of power problems. Over heating of components due to voltage swell is also avoided by using AVR. The switching losses are also reduced as only one arm among three arms is maintained at higher power frequencies depending on mode of operation. Moreover, there is no need to use large capacitor as a result the overall size of converter is also reduced. Hence, the output voltage of the AVR can be maintained at the specified voltage. Hence, the AVR is cost can be reduced, and the efficiency of the power convertor can be extended.

Index Terms—AC boost converter, ac buck converter, automatic voltage regulator (AVR).

I. Introduction

Power quality determines the fitness of electrical power to consumer devices. Synchronization of the voltage frequency and phase allows electrical systems to function in their intended manner without significant loss of performance or life. One of the important issues in maintaining power quality is voltage regulation. In this paper a novel three arm AVR is proposed which maintains constant load voltage during under and over voltages. Tap changer autotransformer is one of the conventional methods to maintain voltage regulation. It is connected between utility and load. With variations in load the tap changer is adjusted and voltage profile is maintained. However, tap-changer autotransformer has some disadvantages like step regulation of the supply voltage, large installation volume, and inability to improve the voltage distortion. Dynamic voltage restorer is another method to maintain voltage profile but it has limitation that it can be used for only over voltages and not for under voltages. AVRs implemented by a three-arm power converter have been reported [1]–[11]. The conventional three-arm AVRs are shown in Fig. 1. Fig. 1(a) shows a double conversion three-arm AVR. The utility voltage is converted into dc by first and second arms and this dc voltage is again converted to ac by second and third arms. As the capacitance of the dc capacitor depends on the power rating of the load, the allowable ripple voltage of the dc bus it is generally several thousands of microfarads. It has drawbacks of lower power efficiency and larger energy buffer i.e. capacitor. Lower power efficiency is due to switching of two or three arms are at higher frequency. Fig. 1(b) shows a transformer-coupled three-arm AVR [9]. Fig. 1(b) shows a transformer-coupled three-arm AVR [9]. 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. The series converter is connected between utility and load which generate voltage opposite to variation in load voltage and maintains constant load voltage. The purpose of coupling transformer is to match voltage level. The shunt converter is connected in parallel to the utility to absorb or deliver a real power for the series converter for sustaining the dc voltage of converter at a preset value. However in this AVR a large-size low frequency transformer and a large dc capacitor are limitations. To avoid using a low-frequency transformer, Fig. 1(c) shows the direct-coupled three-arm AVR [17], [18].

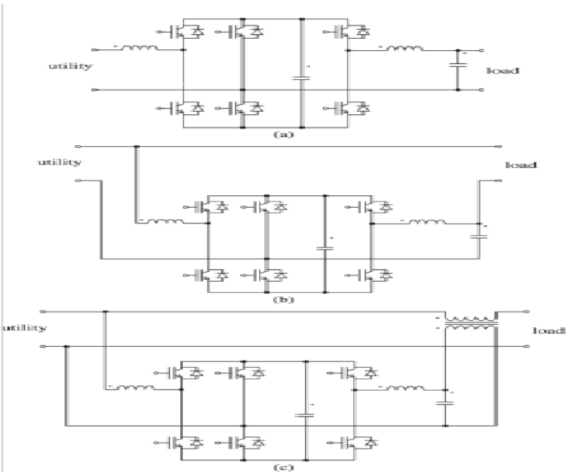

Fig.1. Conventional three-arm AVRs: (a) double-conversion three-arm AVR, (b) transformer-coupling three-arm AVR, and (c) direct-coupled three-arm AVR.

To avoid using a low-frequency transformer, Fig. 1(c) shows the direct-coupled three-arm AVR [10], [11]. Its configuration and operation is similar to transformer coupled three-arm AVR. But the series converter is connected in series with load. However, the size of energy buffer is still large. The proposed three-arm AVR requires only a single conversion. When the utility voltage is lower than the specified voltage this three arm AVR act as an ac boost converter, and when the utility voltage is higher than the specified voltage it acts as buck converter. 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 is required. In comparison with the conventional three-arm AVR with a constant dc bus voltage, the dc bus voltage of the proposed three-arm AVR is a full-wave rectified voltage.

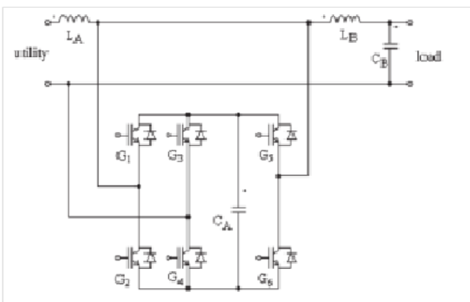

Fig 2: Circuit configuration of the proposed three-arm AVR.

Hence, the use of a large dc capacitor in sustaining a constant dc voltage is avoided, and only a small dc capacitor is employed to act as a snubber and filter circuit. Consequently, the proposed three-arm AVR has the advantages of reduced installation cost and volume, as well as increased reliability and power efficiency.

II. 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 converter acts as buck mode or boost mode and maintain constant amplitude. 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 [1]–[11] with a constant dc voltage.

2.1 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. Fig. 3 shows the operating circuit of the proposed AVR under the ac boost mode. The inductor *LA* is applied as the energy storage element when the three-arm power converter operates as an ac boost converter. Fig. 3(a) shows the operating circuit of the ac boost converter when the utility voltage is in the positive half-cycle. As shown in Fig. 3(a), *G*1 and *G*6 are always on, and *G*2 and *G*5 are always off. When *G*3 is on and *G*4 is off, the inductor *LA* is energized through the utility, *G*1 and *G*3. In this duration, the inductor voltage (*v*LA) is given by

$$vLA=vS \quad (1)$$

where *vS* is the utility voltage. The current of the inductor *LA* is increased. The energy stored in the inductor *LA* will be released through *G*1 and *G*4 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

$$vLA=vS-Vc \quad (2)$$

where *vC* is the dc bus voltage of the three-arm power converter. As the converter voltage is higher than utility voltage under the ac boost mode, the current passing through the inductor *LA* is decreased. When the current passing through the inductor *LA* is continuous, by applying Faraday's law, the voltage-second balance can be represented as

$$vsDT + (vS\text{-}vc)\,(1\text{-}D)\,T=0 \quad (3)$$

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

$$Mv=Vc/vS=1/(1\text{-}D) \quad (4)$$

Fig. 3(b) shows the operating circuit while the utility voltage is in the negative half-cycle. As shown in Fig. 3(b) 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 efficiency of the dc/dc boost converter is dependent on the duty ratio as shown in(5)
The ripple of the input current can be derived as

$$\Delta iLA = vsD/LAf \tag{5}$$

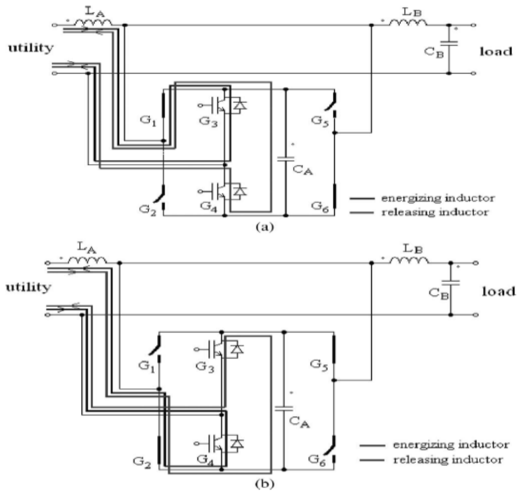

Fig. 3. Operating circuit of the proposed AVR under the ac boost mode. (a) Positive half-cycle. (b) Negative half-cycle.

where *f* is the switching frequency. The ripple of the input current is dependent on the duty ratio, switching frequency *f*, and inductor *LA*. In the continuous conduction mode, the minimum product of *LA* and *f* can be derived as

$$(LAf)\ \min = D\ (1-D)^2\ Z/2 \tag{6}$$

where *Z* is the load.

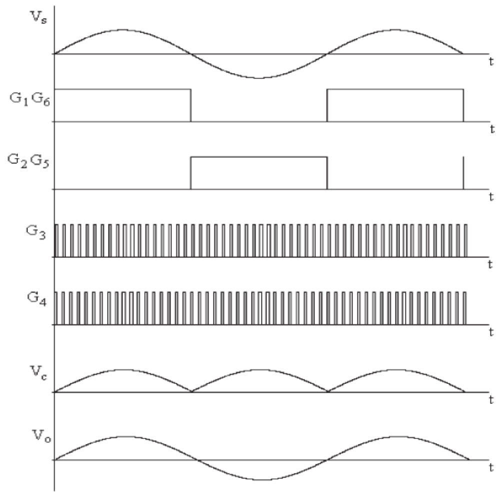

Fig. 4. Related control signals of the power

Hence, the inductor *LA* 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 *CA* and output filter (*LB*, *CB*) form as a third-order low-pass filter to filter out the switching harmonic in the output voltage. Hence, a lower capacitance dc capacitor *CA* of several tens of microfarads can be selected.

2.2 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 *LB* 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. 6(a), *G*1 and *G*4 are always on, while *G*2 and *G*3 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 *LA* and the dc capacitor *CA* performed as a low-pass filter. When *G*5 is on and *G*6 is off, the inductor *LB* is energized from the rectified utility voltage through *G*4 and *G*5. In this duration, the inductor voltage (*v*LB) can be represented as

$$vLB = vc - vo \tag{7}$$

where *vo* is the load voltage. Since the rectified utility voltage is higher than the load voltage, the current passing through the inductor *LB* will be increased, and it stores energy in this duration. The energy stored in the inductor *LB* will be released to the load through *G*4 and *G*6 when *G*5 is off and *G*6 is on, and the inductor voltage is

$$vLB = -v0 \tag{8}$$

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

$$(vC-v0)DT + (-v0)\ (1-D)\ T \tag{9}$$

where D and T are the duty ratio and switching period of G6, respectively. From (9), the dropped gain can be derived as

$$Mv = v0/vC = D \tag{10}$$

Since the input inductor LA and the dc capacitor CA form a low-pass filter, the rectified voltage of the three-arm power converter is close to the absolute utility voltage.

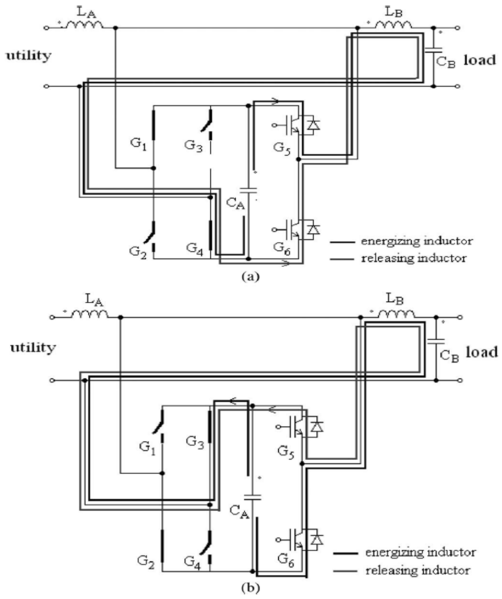

Fig. 5. Operating circuit of the proposed AVR under the ac buck mode (a) Positive half-cycle. (b) Negative half-cycle.

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 *LB* 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 *LB* 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 as that in (15). As shown in (15), the load voltage is lower than 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 (3) 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. Since the voltage across the inductor *LA* is smaller than that of the conventional three-arm AVR, the inductance of the inductor *LB* in the proposed AVR can be reduced.

The ripple of the input current can be derived as

$$\Delta iLA = (vC - v0)\, D/LBf \qquad (11)$$

In the continuous conduction mode, the minimum product of *LB* and *f* can be derived as

$$(LBf)\ min = (1-D)\ Z/2 \qquad (12)$$

Hence, the inductance of the inductor *LB* can be determined by the switching frequency, specified ripple current, range of the duty ratio, and load. The ripple of the output voltage can be derived as

$$\Delta v0 = v0\ (1-D)/8LBCBf^2 \qquad (13)$$

The capacitor *CB* can be determined for a specified output ripple voltage. As shown in Fig. 5, the input inductor *LA* and the dc capacitor *CA* form a low-pass filter to filter out the switching harmonic in the input current. In discontinuous conducting mode of inductor current amplifier duty ratio is slightly reduced. However, this problem can be solved effectively by a close-loop control of the output voltage. In discontinuous mode the output voltage deviate from its desired value and the controller of the output voltage can correct the duty ratio to trace the desired value. In the proposed AVR either second or third arm is at high frequency switching.

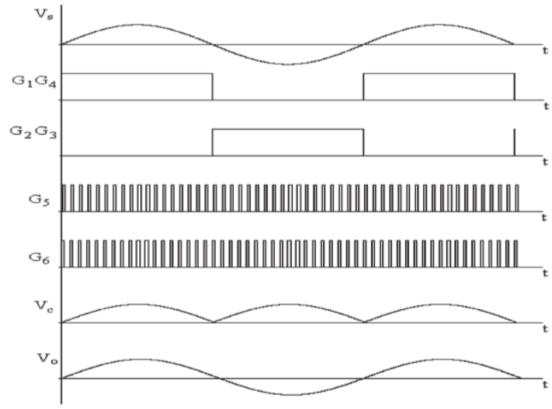

Fig. 6. Related control signals of the power electronic switches and voltage waveforms of the proposed AVR under the ac buck mode.

As only one arm is at high frequency switching losses can be reduced. The size of inductor and capacitor are also small. Hence cost and volume of installation are low.

III. 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 processing unit is employed to generate a low-frequency square signal and a selecting signal. 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 to obtain the driving signals of *G*1 and *G*2 of the first arm. The detected utility voltage is also sent to a selecting circuit to generate a selecting signal *C*1. The selecting signal $C1$ determines the operation mode of the three-arm power converter. If the utility voltage is lower than the specified voltage, the selecting signal $C1$ is HIGH for operating at the ac boost mode. On the contrary, the selecting signal $C1$ is LOW for operating at the ac buck mode when the utility voltage is higher than the specified voltage.

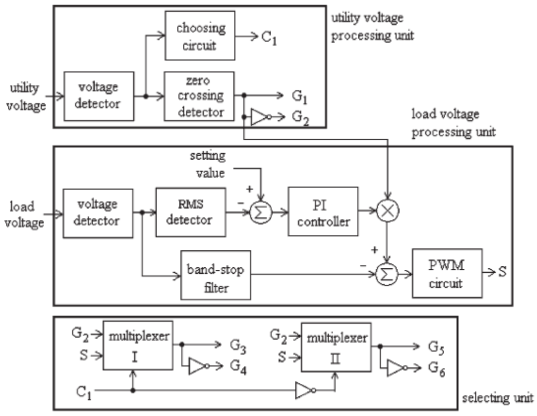

Fig. 7. Control block of the proposed three-arm power converter.

The detected load voltage is sent to a band-stop filter with a center frequency of 60 Hz to detect the distorted signal of the load voltage. The output of the band-stop filter and the adjustable square-waveform signal are sent to a subtractor.

TABLE I
MAIN PARAMETERS OF PROPOSED AVR

Specified load voltage	110V, 60Hz	PWM switching frequency	20kHz
DC capacitor C_A	20μF	Output filter capacitor C_B	20μF
Input inductor L_A	0.4 mH	Output filter inductor L_B	0.4 mH

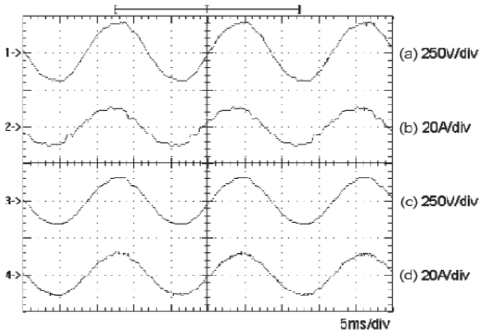

Fig.8. Experimental results of the proposed AVR under a utility voltage of 143 V and resistive load. (a) Utility voltage (b) Utilitycurrent (c) Load voltage (d) Load current.

IV. Simulink Of AVR

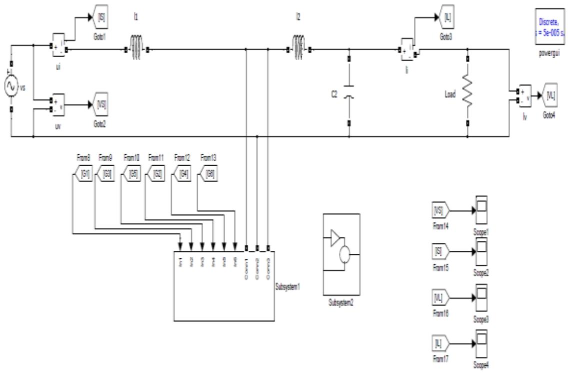

Fig 9: shows the simulink of proposed AVR. It includes source, subsystem1, subsystem2, and load.

V. Experimental results

In order to verify the performance of the proposed AVR is developed. Table I shows the main parameters of the proposed AVR. The capacitance of the dc capacitor CA is only 20 μF, it is very small in comparison with that of the dc capacitor used in the conventional three-arm AVR [1]–[11]. Fig. 9 shows the experimental results of the proposed AVR under the utility voltage of 143 V and a resistive load. Fig. 10 shows the experimental results of the proposed AVR under the utility voltage of 77 V and a resistive load. Fig. 11 shows the experimental results of the proposed AVR under the utility voltage of 121 V and nonlinear load It can be found that the output voltage varied between 113 and 108.9 V upon varying the utility voltage from 77 to 143 V.

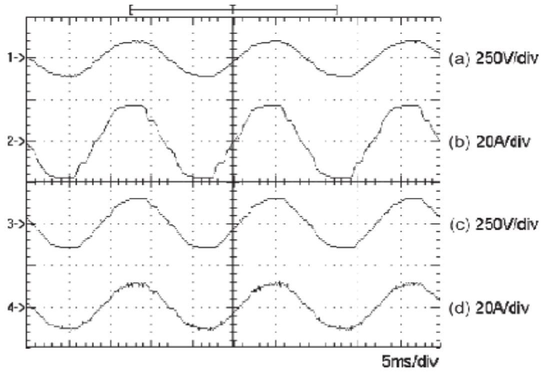

Fig.10. Experimental results of the proposed AVR under a utility voltage of 77 V and resistive load. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current.

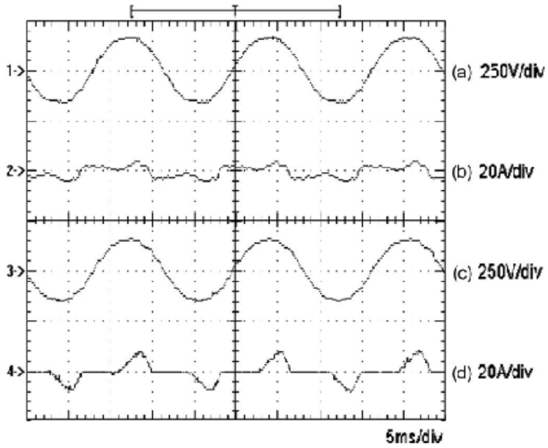

Fig. 11. Experimental results of the proposed AVR under a utility voltage of 121 V and nonlinear load. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current.

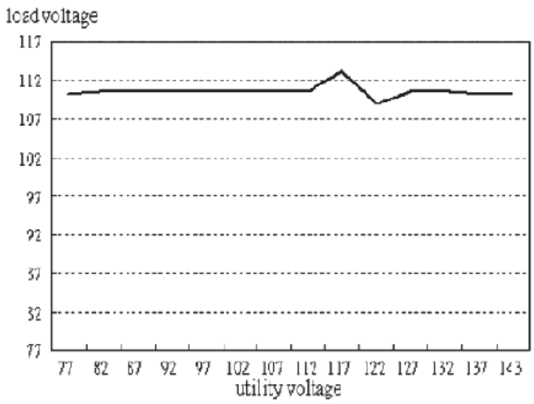

Fig12: Experimental results of the load voltage for the proposed AVR upon varying the utility voltage from 77 to 143 V.

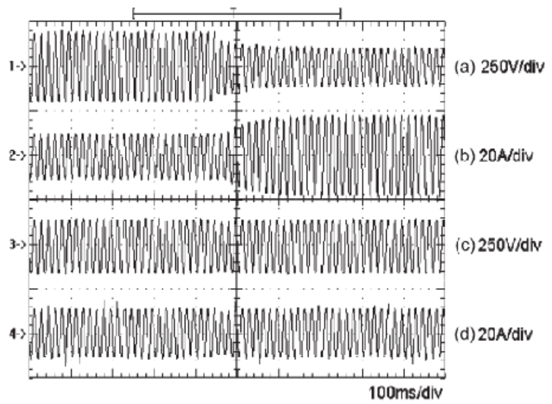

Fig13: Experimental results of the proposed AVR upon changing the utility voltage abruptly from 143 to 77 V. (a) Utility voltage. (b) Utility current.
(c) Load voltage. (d) Load current.

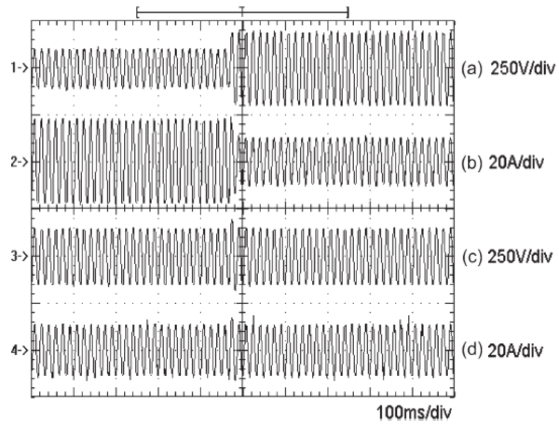

Fig14: Experimental results of the proposed AVR upon changing the utility voltage abruptly from 77 to 143 V. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current.

VI. Conclusion

In this paper three arm ac automatic voltage regulator (AVR) is proposed. This power converter acts as an ac boost converter when the load voltage decreases and acts as a buck converter when load voltage increases. The components can be protected from overheating due to voltage swells. The efficiency of converter is improved as only one arm is at higher frequency. It is relatively inexpensive as size is also reduced. The experimental results verify that the performance of the proposed AVR is as expected.

REFERENCES

[1] Z. J. Zhou, X. Zhang, P. Xu, and W. X. Shen, "Single-phase uninterruptible power supply based on Z-source inverter," *IEEE Trans. Ind. Electron.*, vol. 55, no. 8, pp. 2997–3004, Aug. 2008.

[2] C. C. Yeh and M. D. Manjrekar, "A reconfigurable uninterruptible power supply system for multiple power quality applications," *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1361–1372, Jul. 2007.

[3] C. B. Jacobina, T. M. Oliveira, and E. R. C. da Silva, "Control of the single-phase three-leg ac/ac converter," *IEEE Trans. Ind. Electron.*, vol. 53, no. 2, pp. 467–476, Apr. 2006.

[4] C. B. Jacobina, I. S. de Freitas, and E. R. C. da Silva, "Reducedswitch-count six-leg converters for three-phase-to-three-phase/four-wire applications," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 963–973, Apr. 2007.

[5] J. M. Chang,W. N. Chang, and S. J. Chiang, "Multilevel single-phase rectifier ∼ inverter with cascaded connection of two three-arm

converters," *Proc. Inst. Elect. Eng. Elect. Power Appl.*, vol. 153, no. 5, pp. 719–725, Sep. 2006.

[6] J. H. Choi, J. M. Kwon, J. H. Jung, and B. H. Kwon, "High-performance online UPS using three-leg-type converter," *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 889–897, Jun. 2005.

[7] H. W. Park, S. J. Park, J. G. Park, and C. U. Kim, "A novel high performance voltage regulator for single-phase ac sources," *IEEE Trans. Ind. Electron.*, vol. 48, no. 3, pp. 554–562, Jun. 2001.

[8] B. H. Kwon, G. Y. Jeong, S. H. Han, and D. H. Lee, "Novel line conditioner with voltage up/down capability," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1110–1119, Oct. 2002.

[9] C. A. Petry, J. C. Fagundes, and I. Barbi, "Study of an ac–ac indirect converter for application as line conditioner," in *Proc. IEEE ISIE*, 2005, vol. 2, pp. 757–762.

[10] S. J. Chiang, C. Y. Yen, and K. T. Chang, "A multimodule parallelable series-connected PWM voltage regulator," *IEEE Trans. Ind. Electron.*, vol. 48, no. 3, pp. 506–516, Jun. 2001.

[11] M. T. Tsai, "Analysis and design of a cost-effective series connected ac voltage regulator," *Proc. Inst. Elect. Eng. Elect. Power Appl.*, vol. 151, no. 1, pp. 107–115, Jan. 2004.