Novel Control of Three-Arm AC Automatic Voltage Regulator with Fuzzy logic Technique.

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Abstract- This paper proposes a novel three-arm AC automatic voltage regulator (AVR) with fuzzy logic technique. A fuzzy controller based AVR has been developed and simulated to reduce the switching losses. The proposed fuzzy controller based AVR has capability of delivering sinusoidal output current with good output voltage regulation. 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. 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 convertor can be extended to analysis Total Harmonic Distortion (THD).

Key Words-- **AC boost converter, ac buck converter, automatic voltage regulator (AVR), Fuzzy logic controller, THD**

1 INTRODUCTION

Currently the Quality of supplied power is important to several customers. Power quality (PQ) is a service and many customers are ready to pay for it. In the future, distribution system operators could decide, or could oblige by authorities to supply their customers with different PQ levels and at different prices. 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 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[1-3]. 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[4-6]. 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. To verify the performance of the proposed three-arm AVR, a prototype is developed and tested.

2. FUZZY SET THEORY

(a)Definition of a fuzzy set: assuming that X is a collection of objects, a fuzzy set A in X is defined to be set of ordered pairs.

$$A = \{(x, \mu_A (x))/x € X\} \qquad (1)$$

Where $\mu_A(x)$ is called the membership function of x in A. The numerical interval X is called Universe of Discourse. The membership function $\mu_A(x)$ denotes the degree to which x belongs to A and is usually limited to values between 0 and 1

(b) Fuzzy set operation: Fuzzy set operators are defined Fuzzy set operators are defined based on their corresponding membership functions. Operations like AND, OR, and NOT are some of the most important operators of the fuzzy sets. It is assumed that A and B are two fuzzy sets with membership functions $\mu_A(x)$and $\mu_B(x)$respectively. Then, the following operations can be defined:

(1) The AND operator or the intersection of two fuzzy sets The membership function of the intersection of these two fuzzy sets ($C = A \cap B$) , is defined by

$$\mu_c(x)= \min\{ \mu_A (x), \mu_B(x)\}, x€ X \qquad (2)$$

(2) The OR operator or the union oftwo fuzzy sets The membership function of the union of these two fuzzy sets($D = A \cup B$), is defined by

$$\mu_D(x)=\max\{ \mu_A (x), \mu_B(x)\}, x€ X \qquad (3)$$

3. FUZZY LOGIC CONTROLLER

Fuzzy control systems are rule-based systems in which a set of fuzzy rules represents a control decision mechanism to adjust the effects of certain system stimuli . The aim of fuzzy control systems is normally to replace a skilled human operator with a fuzzy rule based system. The fuzzy logic controller provides an algorithm, which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Figure 1 illustrates the basic configuration of a fuzzy logic controller, which consists of a fuzzification interface, a knowledge base, a decision-making logic, and a defuzzification interface[7].

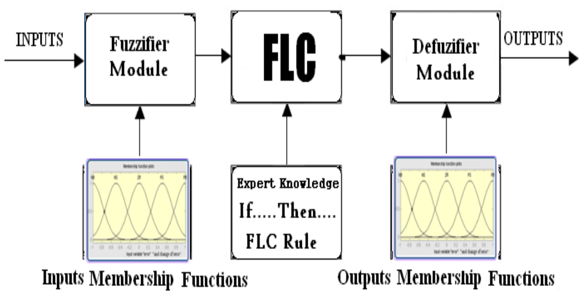

Figure 1: Design of Fuzzy Logic Controller

4. FUZZY-BASED AVR

The first step in designing a fuzzy-based AVR is to choose which state variables, representative of system dynamic performance, must be taken as the input signals to the controller. The second step is to choose the linguistic variables, keeping in mind that the number of linguistic variables specifies the quality of the control. As the number of the linguistic variables increases, the computational time and required memory also increase. Therefore a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. For the test systems, following seven linguistic variables for each of the input and output variables are used to describe them:
(i)LP (Large Positive), (ii) MP (Medium Positive), (iii)SP (Small Positive), (iv) ZR (Zero), (v) SN (Small Negative), (vi) MN (Medium Negative) and (vii) LN (Large Negative). The normalization of the input variables is done by dividing the input values by maximum of the corresponding value of the input variable obtained by open loop simulation. Thirdly, it is required to determine the membership functions for the fuzzy sets. In this paper, the authors have used Fuzzy control systems are rule-based systems in which a triangular membership functions to define the degree of membership as shown in Figure 2.

In designing the AVR, the rules are defined using linguistic variables. The two inputs, deviation of error and its derivative, result in 49 rules for each machine. A proper way to show these rules is given in Table 1. A typical rule has the following structure:

Rule 1. IF voltage error is LN (Large Negative) AND derivative of error is LN (Large Negative) THEN VAVR (Output of fuzzy AVR) is LP (Large Positive)

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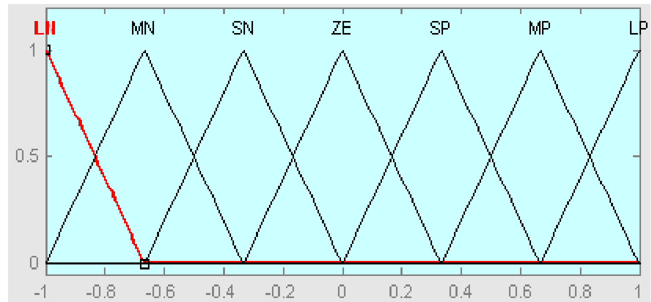

Figure 2: Triangular Membership Function of Input and Output Variables

In this paper, the Mmn-Max method is used to find the fuzzy region for each fuzzy rule. Fuzzy rules are connected using AND operator, where the AND operator means finding minimum between two membership functions[1].

Control e \ Δe	NL	NM	NS	ZR	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	NL	NL	NM	NM	NS	NS	NS
NS	NL	NM	NM	NS	NS	NS	ZR
ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
PS	ZR	PS	PS	PS	PM	PM	PL
PM	PS	PS	PS	PM	PM	PL	PL
PL	PL	PL	PL	PL	PL	PL	PL

Table 1: Fuzzy Rules Table

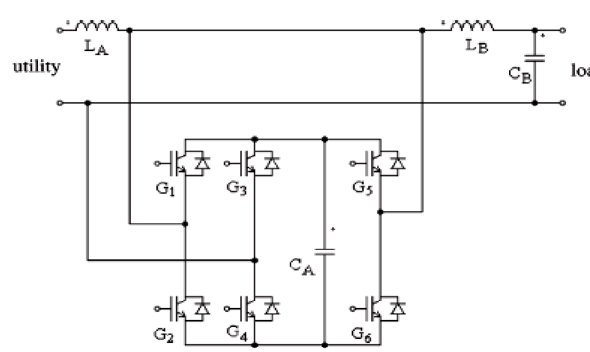

Fig.3 Circuit configuration of the proposed three-arm AVR.

5. SYSTEM CONFIGURATION AND OPERATION THEORY

The circuit configuration of the proposed three-arm AVR is shown in Fig. 3. This AVR comprises a three-arm power converter, an input inductor, a small dc capacitor, and an output filter. 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[8]. 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.

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. Fig. 4 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. 4(a) shows the operating circuit of the ac boost converter when the utility voltage is in the positive half-cycle. As shown in Fig. 4(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

$$v_{LA} = v_s \qquad (4)$$

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

$$v_{LA} = vs - vc \qquad (5)$$

Where *vc* 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 *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

$$V_sT - V_cT\ (1–D) = 0 \qquad (6)$$

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 $M_v = 1/\ 1\text{-}D$ (7)

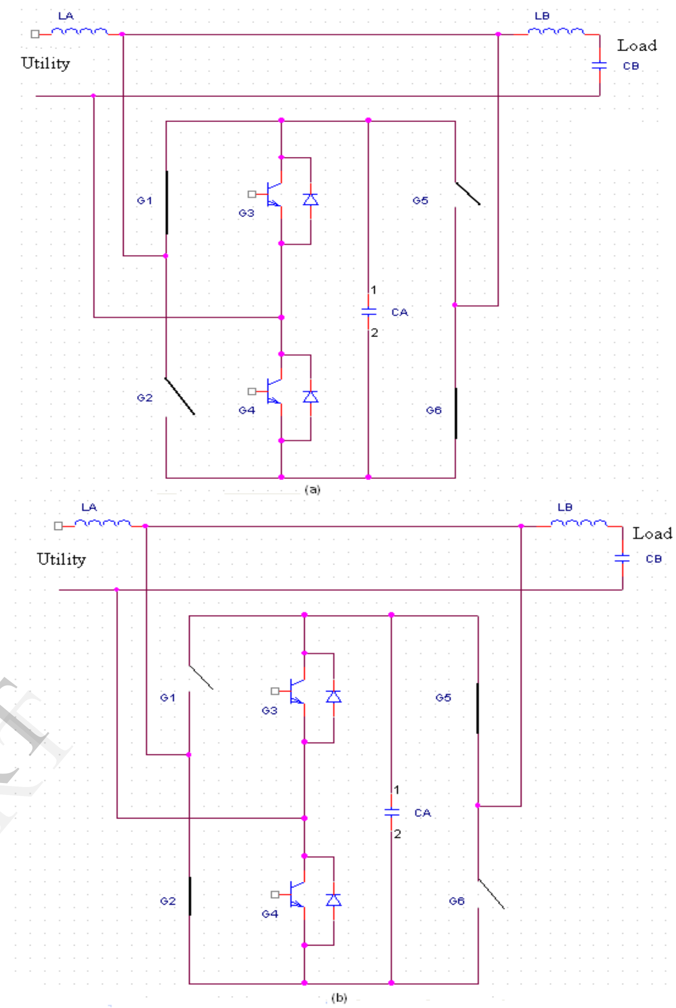

Fig. 4. Operating circuit of the proposed AVR under the ac boost mode. (a) Positive half-cycle. (b) Negative half-cycle[2]

The operation of the three-arm power converter is similar to the dc/dc boost converter during the positive half-cycle. Fig. 4(b) shows the operating circuit while the utility voltage is in the negative half-cycle. As shown in Fig. 4(b) and the amplifier gain is also the same as (7). As shown in (7), 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[9]. The ripple of the input current can be derived as

$$\Delta i_{LA} = v_sDT/\ L_A \qquad (8)$$

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

$$(L_A)\ min=D(1-D)^2Z/2f \qquad (9)$$

Where *Z* is the load. 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. 4, 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[10-12].

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 *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

$$V_{LB} = vc\text{-}v_0 \qquad (10)$$

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

$$V_{LB} = -v_0 \qquad (11)$$

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 inductor *LB* is used, the voltage-second balance can be represented as

$$VcDT - v_oT = 0 \qquad (12)$$

Where *D* and *T* are the duty ratio and switching period of *G*6, respectively. From (7), the dropped gain can be derived as

$$M_v = D \qquad (13)$$

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. 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 (13). As shown in (13), the load voltage is lower than the dc bus voltage of the three-arm power converter [13].

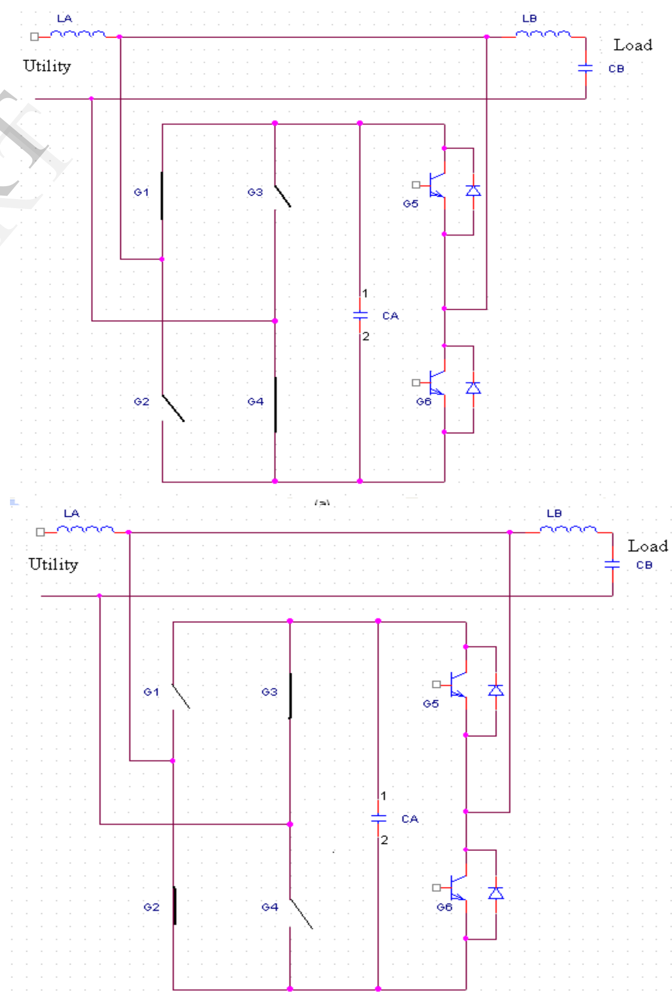

Fig. 5. Operating circuit of the proposed AVR under the ac buck mode. (a) Positive half-cycle. (b) Negative half-cycle.[2]

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 (4) 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.

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

$$(L_B)_{\min} = (1 - D)Z/2f. \tag{14}$$

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

$$\Delta vo = (V_c - V_o)D/8L_B C_B f^2. \tag{15}$$

6. TEST SYSTEM

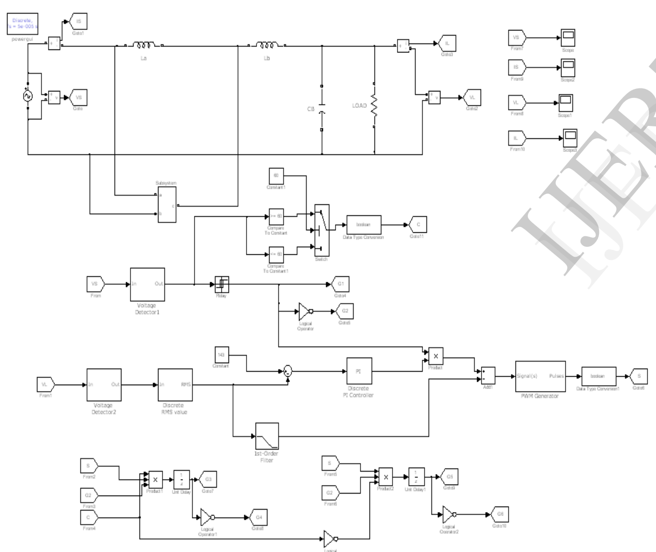

Fig 6 Fuzzy Controller Based Three-Arm Automatic Voltage regulator(test system)

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

Table 2 Main parameters of proposed avr[2]

Fig. 6 shows test system 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 *C*1 determines the operation mode of the three-arm power converter. If the utility voltage is lower than the specified voltage, the selecting signal *C*1 is HIGH for operating at the ac boost mode. On the contrary, the selecting signal *C*1 is LOW for operating at the ac buck mode when the utility voltage is higher than the specified voltage.

7. RESULTS

In order to verify the performance of AVR a fuzzy based AVR model has been developed and simulated. Fig 7 shows the results of the proposed AVR under a utility voltage of 143 V and resistive load. This is test system 1.The load voltage is sinusoidal which is regulated 110V. Fig 8 shows the results of the proposed AVR under a utility voltage of 77 V and resistive load. This is test system 2.The load voltage is sinusoidal which is regulated 110V.Fig 9 shows the results of the proposed AVR under a utility voltage of 121 V and nonlinear load. In this test system 3 the load current not completely distorted and load voltage is regulated at 110V. Fig.10 shows the results of the proposed AVR upon changing the utility voltage abruptly from 143 to 77 V.In this test system 4 the load voltage is regulated at 110V. Fig. 11 shows the results of the proposed AVR upon changing the utility voltage abruptly from 77 to 143 V.In this test system 5 also the load voltage is regulated at 110V.By using fuzzy controller based AVR we can reduce the %THD in the load current, which is shown in the table 3.

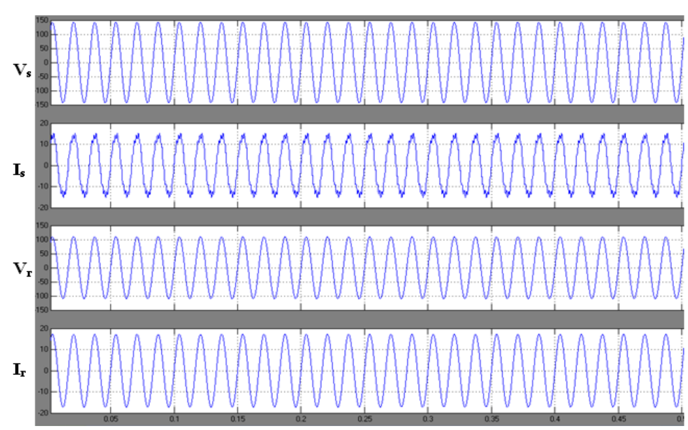

Fig. 7. Results of the proposed AVR under a utility voltage of 143 V and resistive load. (a) Utility voltage. (b) Utility current. (c) Load voltage.(d) Load current

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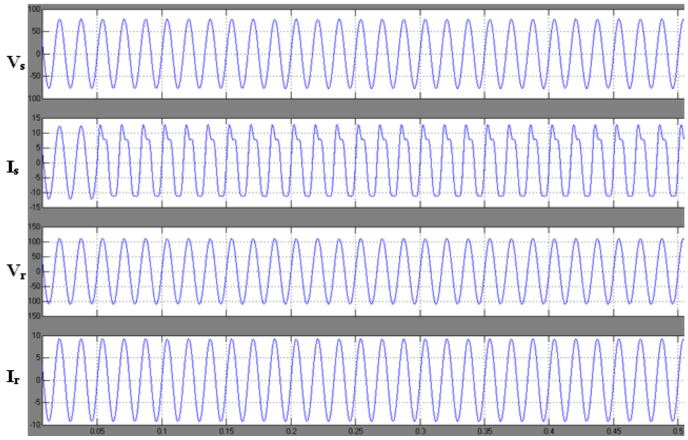

Fig. 8. Results of the proposed AVR under a utility voltage of 77 V and resistive load. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current

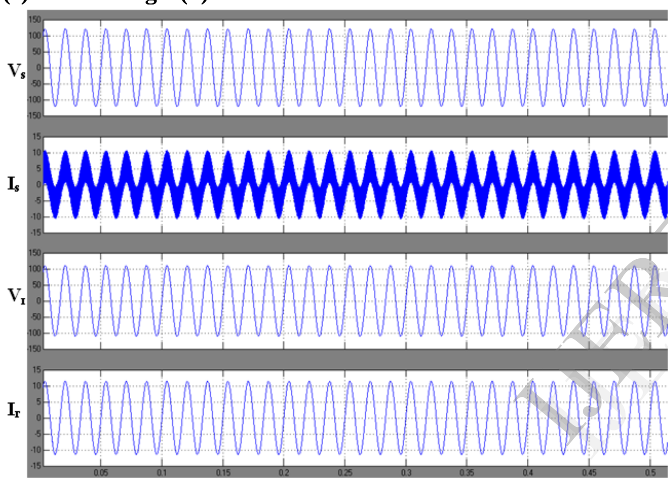

Fig. 9. Results of the proposed AVR under a utility voltage of 121 V and nonlinear load. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current

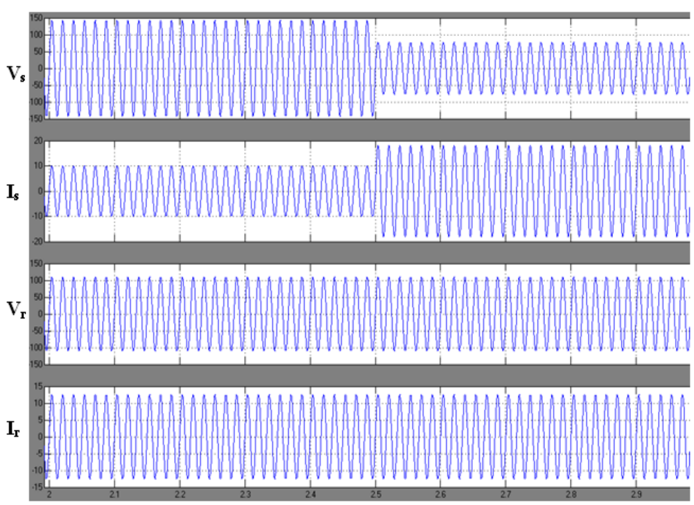

Fig. 10. Results of the proposed AVR upon changing the utility voltage abruptly from 143 to 77 V. (a) Utility voltage. (b) Utility current. (c) Load voltage. (d) Load current.

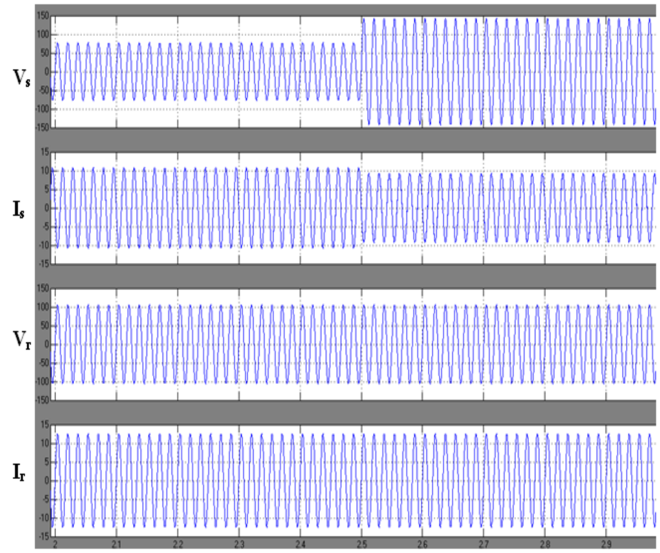

Fig. 11. Results of the proposed AVR upon changing the utility voltage abruptly from 77 to 143 V. (a) Utility voltage. (b) Utility current. C) Load voltage. (d) Load current

S. NO	NO OF TEST SYSTEM	WITH PI CONTROLLER	WITH FUZZY CONTROLLER
1	Test system 1	11%	2%
2	Test system 2	21%	2%
3	Test system 3	70%	0.1%
4	Test system 4	2.3%	0.05%
5	Test system 5	2.3%	2%

Table 3 % THD in load current

8.CONCLUSION

A novel fuzzy based 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. 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.

The closed loop control schemes of direct current control, for the proposed AVR with fuzzy controller have been described. A suitable mathematical have been described which establishes the fact that in both the cases the compensation is done but the response of fuzzy controller is faster and the THD is minimum for the both the voltage and current. Proposed model for the AVR is to compensate input voltage harmonics and current harmonics caused by nonlinear load. The work can be extended to compensate the supply voltage and load current imperfections such as sags, swells, interruptions, voltage imbalance, flicker, and current unbalance. By using fuzzy controller instead of PI controller we can reduce %THD in the load current shown in table 3.

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