Automatic Voltage Regulator with Series Compensation

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Abstract* — *An Automatic voltage regulator (AVR) based series compensation is described in this paper. An AC chopper is used here for producing the compensation voltage. The AC chopper is based on pulse width modulation technique (PWM).The switching pattern of AC chopper will reduce the commutation problems. The direct AC-AC conversion present here will reduce the requirement of energy storage devices. It has the ability to compensate both voltage sag as well as the spikes. The control section is developed using artificial neural network.

Keywords - *Component, AVR, Series compensation, PWM*

I. Introduction

In recent years, there has been an increased emphasis on, and concern for, the quality of power delivered to factories, commercial establishments, and residences [1]. This is due to the preponderance of harmonic-creating systems in use. Adjustable-speed drives, switching power supplies, arc furnaces, electronic fluorescent lamp ballasts, and other harmonic-generating equipment all contribute to the harmonic burden the system must accommodate. In addition, utility switching and fault clearing produce disturbances that affect the quality of delivered power. Much of the equipment in use today is susceptible to damage or service interruption during poor power-quality. Power quality problems are mitigated by equipments like power conditioners.. By employing power conditioning equipment such as voltage regulators and uninterruptible power supplies, problems at the utility side may be prevented from distorting the voltage at the load side[1].

There are various power quality problems on the utility side: Voltage sags, voltage swells, transients, voltage interruptions, etc. Power quality is quite frequently described as "voltage quality. Also, power quality can be defined with respect to "clean power." "Clean power" refers to power that has sinusoidal voltage without any distortion and which is at the desired magnitude and frequency. "Power quality" is important and necessary especially for sensitive electronic devices designed and manufactured in state-of-the-art technology. Non-electronic equipments used in the past such as motors, incandescent lights, and resistance heaters could tolerate voltage disturbances of ±5 % of nominal voltage. Power line disturbances can cause serious problems to sensitive equipment such as computers, communication equipment and process control systems. With an increase in the use of sensitive equipment, voltage sag and swell have been identified as important power quality problems facing industrial customers today.

The source of 85% of all voltage events, caused by inadequate supply, undersized wiring, or an overloaded circuit, originated within a facility, not on the electric utility system. Frequently, problems arise when equipment turns "on" or "off" on the same circuit. Environmental changes, such as lightning storms, high winds, flooding, physical damage, utility operations, or neighboring facilities, also can affect voltage.

II. Operating Principle

The electric circuit of the automatic voltage regulator is shown in Figure 1. The AVR generates the compensation voltage Vco using the buck topological operation.S1, S2, S3 and S4 are switches of the AVR. T is a three winding transformer used for series compensation according to the input voltage Vi and is also stabilize the output voltage v_o. N_{P1} and N_{P2} are the number of primary winding turns, where N_{P1}=N_{P2}, and N_S is the number of secondary winding turns. The primary winding of the transformer has a centre tap. The filter capacitor voltage V_C is transformed into V_{CO} through T. V_r is the chopper modulated voltage and V_L is the inductor voltage. The AVR system uses PWM controller to generate and modulate the PWM signals, and control the output of the AC chopper. Here two TRIAC's $S_{b1}$and S_{b2} or back-to-back connected thyristors are used for series compensation according to the polarity of input voltage. It offers a bidirectional current flow. If a short circuit condition occurs, a large current may be passing through the primary of the transformer and may affect the operation of automatic voltage regulator. Also this high current should passes through the ac chopper section and resulting a high switching stress, sometimes it may destroy the switches. So additional bypass switches are provided for safe operation of AVR.

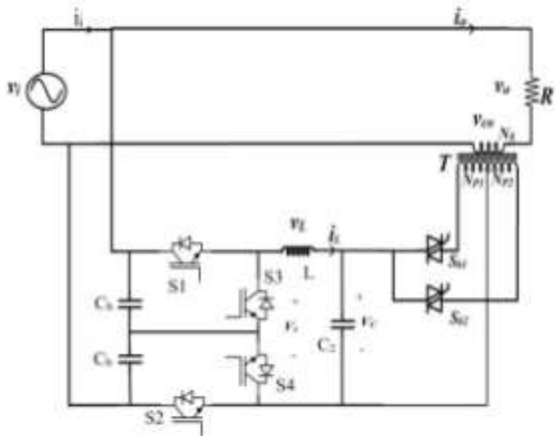


Fig.1. Automatic voltage regulator

When a short circuit occurs, the bypass circuit composed of bypass switches carries the secondary current of the transformer. Thus, the short-circuit current circulates through the bypass switches. Using the bypass switches, the proposed AVR can compensate not only for the sag but also for the swell of the input voltage. When the sag is detected, the AVR operates under the voltage sag condition. Under the voltage sag condition, the voltage Vco is in phase with V_{in}. S_{b1} is turned on and S_{b2} is turned off. Then, V_{CO} is added to the input voltage, so the AVR can compensate the voltage sag.

When the swell is detected, the AVR operates under the voltage-swell condition. Under the voltage-swell condition, the voltage Vco is out of phase with Vin.S_{b1} is turned off and S_{b2} is turned ON. So the injection voltage is injected through S_{b2}. The electric circuit of the ac chopper used in the proposed AVR is shown in Figure 2.

This AC chopper consists of four switches, an inductor and capacitors. The output voltage can be controlled by the duty ratio of the chopping pulse. The low-pass filter is used to filter the harmonic components of the output of the AC chopper. L is the filter inductance, is the filter capacitance and R_L is the equivalent resistance of the AC chopper. Owing to the energy stored in the inductance, input filter capacitors C_b are added directly to power semiconductor switches and absorb the energy.

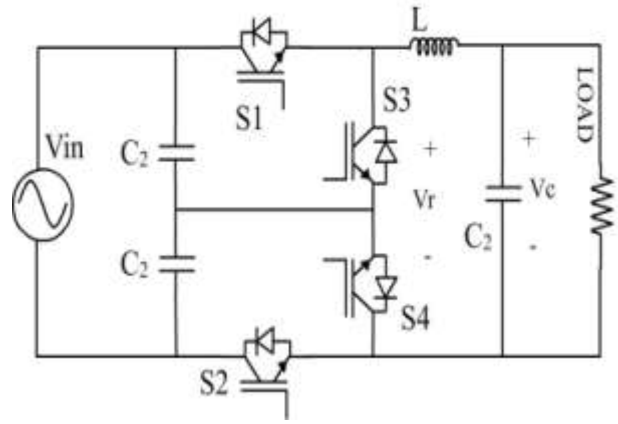


Fig.2. Electric circuit of the ac chopper

The AC chopper provides direct AC –AC conversion without energy storage elements such as a smoothing inductor or a smoothing capacitor. Thus, the size and cost of the AVR are reduced. The AC chopper compensates for only the deviations from the required voltage, so the switches have reduced ratings and stresses compared with AVRs that handle 100% of the system power capability.

A. *Operating Modes*

The output voltage is controlled by changing the duty ratio of the drive signals. The switching patterns are decided by the polarity of the input voltage in the AVR. The drive signals for the switches are shown in table 1.

Table1: The drive signals for the switches

Input State	Mode	S1	S2	S3	S4
Vi > 0	1	ON	ON	OFF	ON
	2	OFF	ON	OFF	ON
	3	OFF	ON	ON	ON
	4	OFF	ON	OFF	ON
Vi < 0	1	ON	ON	ON	OFF
	2	ON	OFF	ON	ON
	3	ON	OFF	ON	OFF
	4	ON	OFF	ON	OFF

During the positive semi cycle of the input voltage, switches S2 and S4 are set to conduct, and switches S1 and S3 are driven by PWM. During the negative semi-cycle of the input voltage, switches S1 and S3 are set to conduct, and switches S2 and S4 are driven by PWM. If all switches are on, a short circuit occurs, and if all switches are off, voltage spikes damage the switches in the AVR. Thus, a switching cycle has a dead time to avoid current spikes of the switches. There are mainly four modes of operation.

Mode 1

This mode is defined when switches S1 and S2 are turned on, as shown in Figure 3. The inductor current i_L conducts through S1 and the diode across S2 for $i_L > 0$as shown in figure 3.3. The inductor current i_L conducts through S2 and the diode across S1 for $i_L < 0$as shown in figure 3.4.i_L conducts through the input and output side, providing energy to the output. As the v_i is higher than the V_c, the current passing through the inductor is increased and energy of the inductor is charged in this mode.

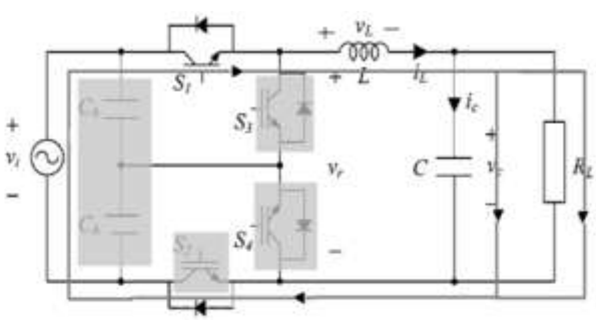


Fig.3.Operating Mode 1:I_L>0

Mode 2

This mode is defined as the Freewheeling mode of positive semi cycles of input voltage which is shown in fig 4.

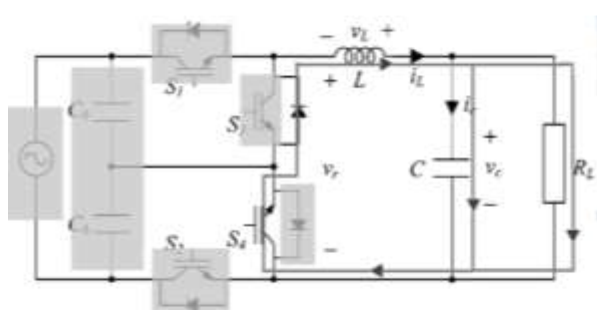


Fig 4.Operating Mode 2 V_i>0; I_L<0

This mode can be called as freewheeling mode. This allows freewheeling action of stored charges in the inductor. The inductor current freewheels through the output side during this period. During the positive half cycle of input voltage, the inductor current freewheels through S4 and diode across S3. Thus, the current passing through the inductor is decreased and the energy stored in the inductor L is discharged.

Mode 3

This mode is complementary to Mode 1. The inductor current i_L conducts through S2 and the diode across S1 for i_L>0as shown in Figure 5. I_L conducts through the input and output side, providing energy to the output. As the V_i is higher than then V_c, the current passing through the inductor is increased and energy of the inductor is charged in this mode. Thus current through the inductor is increased in negative half cycle. This mode is the active mode of negative half cycle.

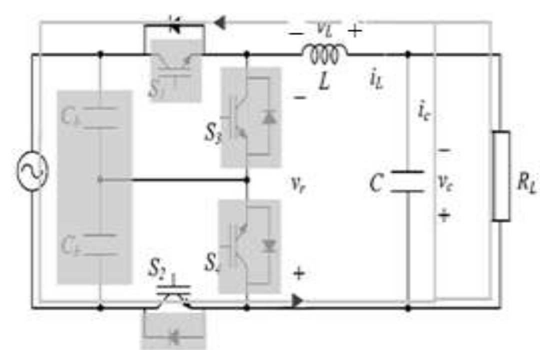


Fig.5.Operating Mode 3:Vi<0 I_L>0

Mode 4

This mode is complementary to Mode 2. The inductor current i_L conducts through S3 and the diode across S4 for i_L<0as shown in Figure 6.In this mode the inductor energy is discharged through the output side.

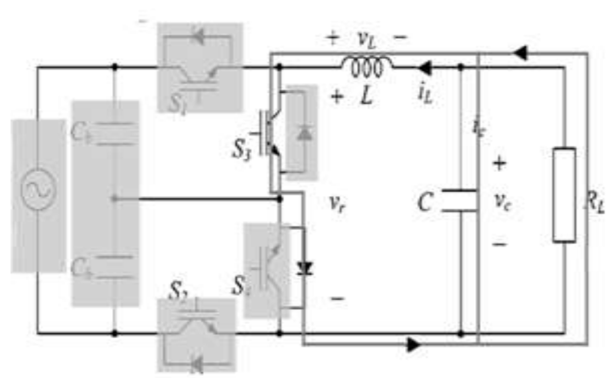
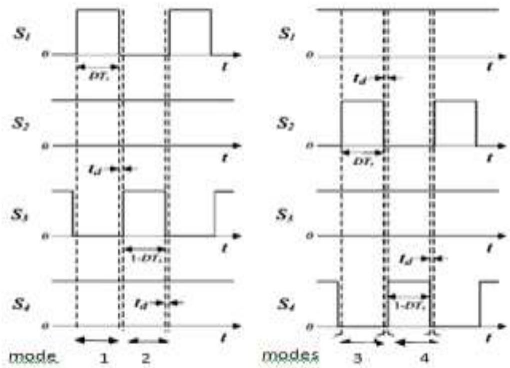


Fig.6.Operating Mode 4:Vi>0 I_L<0

B. *Gating Patterns*



a. Positive half cycle, b. Negative half cycle
Fig.7.Gating Pattern

The switches are triggered in accordance with the polarity of the input sine wave. The duty cycle administered by the controller makes the converter to produce the chopped AC voltage, which in turn is filtered and passed through TRIAC'S.

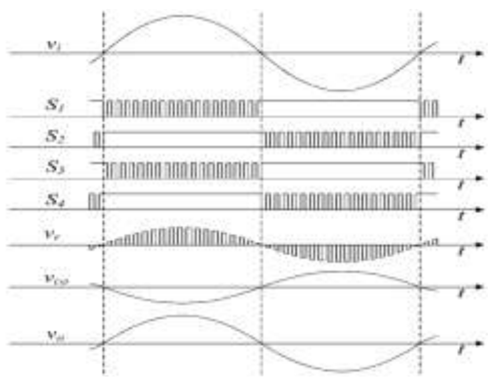


Fig.8. Input, Output and Switching waveform for voltage swell mode

It may be noted that the polarity of the compensation voltage V_{CO} differ in polarity in both sag and swell mode. This compensation voltage is injected using the series transformer to form the compensate voltage at load terminal of rated magnitude.

C. *Control strategy*

The control scheme for the AC chopper is implemented using Artificial neural network. It is a computational model inspired by human brain in which the system used for control is trained by ANN.An Artificial neural network consist of number of artificial neurons that are arranged in layers. Here the duty ratio corresponding to the output voltage is need to be controlled. So optimum angles in each output voltage is trained using Back propagation algorithm. The Back propagation algorithm is used for layered feed forward networks. The input signals are sending forward and the errors are backwards. The network receives input from the neuron present in the input layer, and output of network is given to the output layer. Between this input and output layer, there will be number of hidden layers. The Back propagation algorithm uses supervised learning. The error is computed in each step and the ultimate goal of Back propagation is to adjust the weights and eliminate the error.

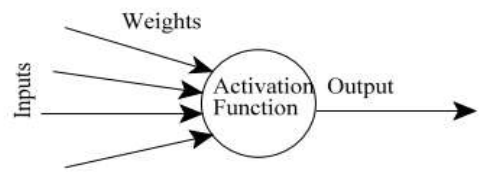


Fig.9.Artificial neuron

Here the output should be maintained constant at a range of input voltage. The duty ratio for switch control at different time is given by the ANN. The signal corresponding to the output voltage is given to the input layer, corresponding duty ratio for switch control are produced at the output layer of ANN. When defining an ANN, it is explained by using the term perceptron as the basic unit instead of a neuron. The perceptron can take several weighted inputs and summarize them, if the combined input exceeds a threshold, it will activate and sent an output. The larger and complex network leads to complex computations. The best approach is to arrange neurons in layers. These multi layer networks has been proven to have capabilities beyond those of single layer

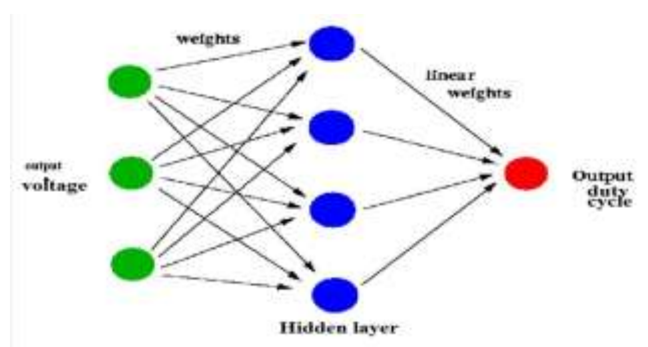


Fig.10. Back propagation algorithm

The simulation was conducted in MATLAB platform.ANN functional block in the MATLAB is used for training the control system of AVR.

III. THEORETICAL ANALYSIS

A Design Equations

The turns ratio of transformer depends on input voltage.The turns ratio is based on percentage of compensation voltage

$$n = \frac{N_s}{N_{p1}} = \frac{N_s}{N_{p2}} = \frac{100 - P_{co}}{P_{co}}$$

Where the percentage of compensation voltage P_{co} given by

$$P_{co} = 100\left(1 - \frac{V_{i,\min}}{V_{nom}}\right)$$

Ripple of inductor current $i_{L;}$

$$\Delta i_L = \frac{v_c(1-D)}{Lf_s}$$

Ripple of capacitor voltage

$$\Delta v_c = \frac{\Delta i_L}{8Cf_s} = \frac{v_c(1-D)}{8LCf_s^{\,2}}$$

IV. SIMULATION AND RESULTS

The automatic voltage regulator using series compensation is done by using matlab. The model consist of an AC to AC converter named as Ac chopper,two TRIACs Which are connected to a three winding injection transformer.So that it can inject the compensating voltage according to the sag and swell.The triac provides a correct polarity to the injection process.Switching pulses for ac chopper aswell as for the TRIACs are generated.There are two controlling schemes are present for each.An artificial neural network control scheme is adopted for providing triggering pulses for switches in ac chopper.Simulation model of Automatic voltage regulator with series compensation is shown in fig 11 and the sub models for gating pulses are shown in fig 12 and fig 13.

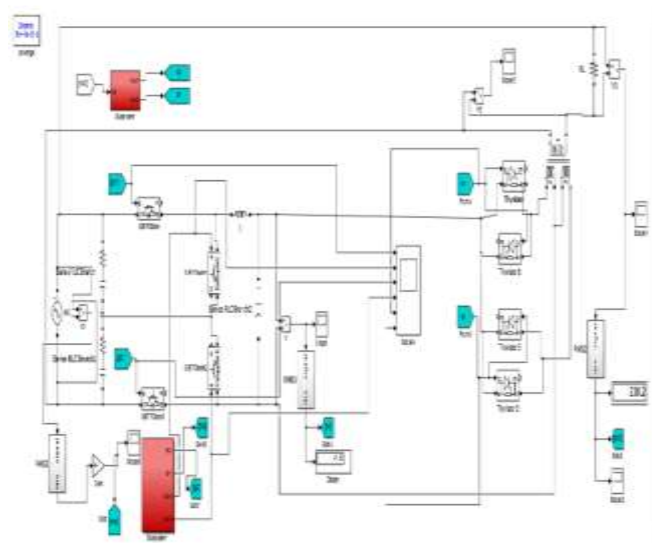


Fig.11. Matlab simulation model for Automatic voltage regulator with series compensation

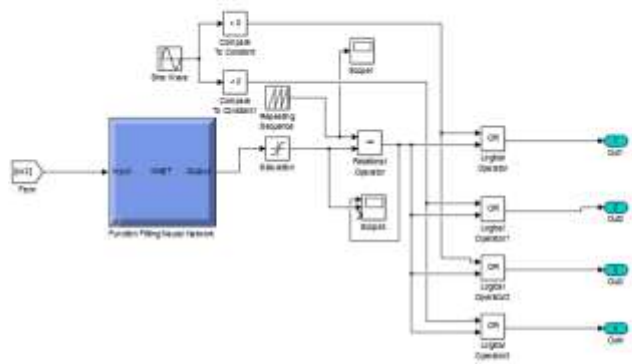


Fig.12. Matlab simulation sub model of artificial neural network for producing gating pulses.

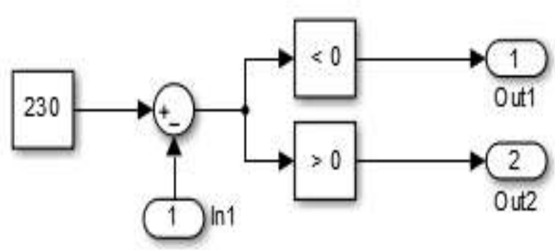


Fig.13. Matlab simulation sub model of TRIACs for producing gating pulses.

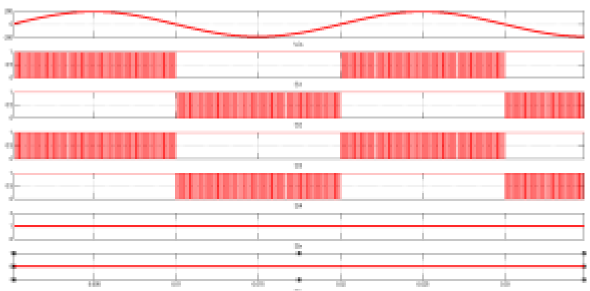


Fig.14. Input voltage and corresponding gating pulses

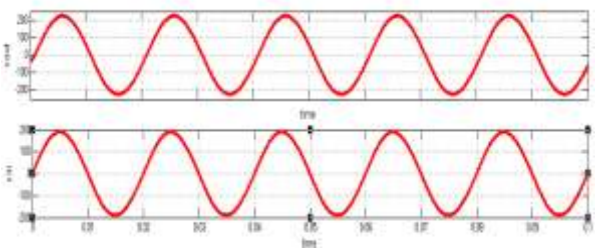


Fig.15. Output voltage and input voltage

Fig 14 shows the switching waveforms of the chopper switches which are determined by the polarity of the input voltage. In fig 15, the input voltage is shown along with output voltage. The input voltage is segmented and then passed through the output filter to get the voltage required for compensation.

V. HARDWARE RESULTS

The hardware unit is shown in Figure 16.The hardware setup is connected to a wire wound resistive load of 100Ω, and the results are taken as shown below.

Fig.16. Hardware Unit

The hardware results for the converter are presented in this section.Figure 17 indicates the chopper output wave form.Figure 18 shows the microcontroller derived pulses to show the matching of the pulses with the theoritical and simulation waveforms. It can be seen that the swiches S1 and S3 are driven by pulse width modulation signal during the positive half cycle of the input voltage , while the pulse of switch S2 are complementary to S1 and S4complementary to S3 . The magnitude of the output pulses from the microcontroller 5 V. The expanded view of the switching pulses are shown.

Fig 17.Chopper Waveform

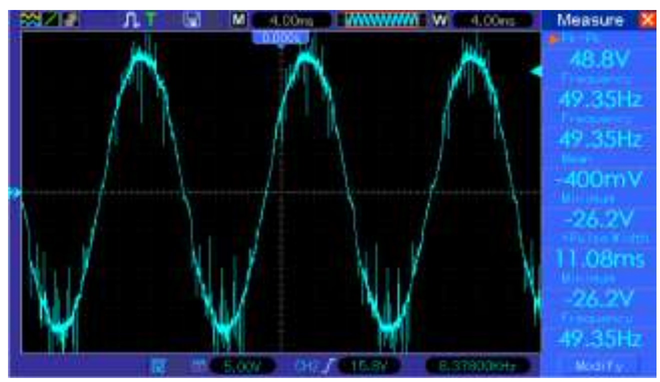


Fig 18.output Waveform

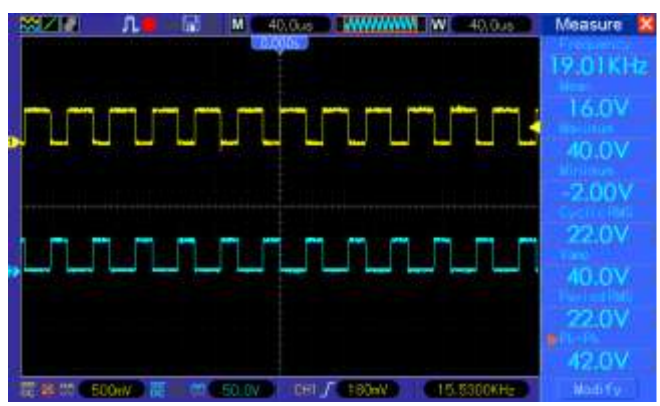


Fig 19.Gating pulse for S1 and S3

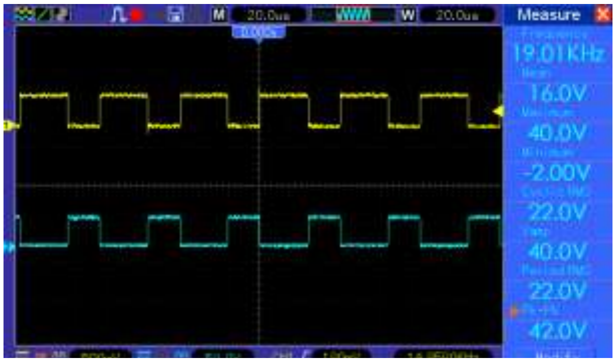


Fig 19.Gating pulse for S2 and S4

V CONCLUSION

This paper proposed an AVR based on series voltage compensation with an ac chopper. The proposed AVR includes a PWM ac chopper and a transformer for series voltage compensation. The ac chopper provides direct ac– ac power conversion. Owing to this feature, the AVR does not require the energy storage elements, so the size and cost of the AVR are reduced. The ac chopper compensates for only the deviations from the required voltage, so the ratings and stresses of the switches have reduced. In the switching patterns, the short circuit is prevented by using dead time. Besides, the current path for the inductor current always exist whatever the current direction, so the commutation problem is solved by switching patterns. Also, using the bypass switches, the proposed AVR can compensate not only for the voltage sag but also for the voltage swell of the input voltage.

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