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Three Phase Static Voltage Regulator Control

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Abstract— **Three Phase Static Voltage Regulator (SVR) is power electronics based device which protects the non-linear, complex loads by maintaining the output voltage within permissible limits irrespective of the voltage sags, voltage swell, transient voltage, harmonics, overvoltage, undervoltage and phase unbalance. When such events occur in power systems the whole system can get collapsed. The operating principle of semiconductor devices/switches in SVR is based on pulse width modulation. The duty cycle of input pulses to these switches is adjusted by using Space Vector Pulse Width Modulation (SVPWM) technique which provides better results over Sinusoidal Pulse Width Modulation (SPWM). This paper proposes the controlling scheme for three phase static voltage regulator using Space Vector Pulse Width Modulation (SVPWM) technique.**

Index Terms— **Direct Component, Inverter Control, Quadrature Component, Rectifier Control, Sinusoidal Pulse Width Modulation (SPWM), Space Vector Hexagon, Space Vector Pulse Width Modulation(SVPWM), Three Phase Static Voltage Regulator.**

I. INTRODUCTION

In power systems voltages are largely affected by large load changes (non-linear/complex loads), capacitor switching. So it is the basic need in power systems to make the output voltages given to load unaffected by the different unwanted events like sags, swells, harmonics, fluctuations. The important point to overcome all these problems is the controlling method used for the operation of switching devices. There are different controlling schemes available like Sinusoidal pulse width modulation, SVPWM etc.

In this paper we have described the most efficient algorithm for SVPWM which requires very less computations and computation time for the proper operation of SVR.

II. THREE PHASE STATIC VOLTAGE REGULATOR

Fig.1 shows the block diagram of SVR. It consists of rectifier, inverter, buck-boost transformer and filter. The basic principle of operation of static voltage regulator is to keep the output voltage i.e. load voltage within permissible limits irrespective of the changes in the input voltage. When the input voltage increases or decreases within certain limit, the control scheme performs the operation in such a way that incoming voltage increases or decreases from its value to acceptable output voltage i.e. provide the energy source to get the required output voltage. This energy source can be implemented by taking the energy from the incoming supply (rectifier). The direction of the current flow as shown in the block diagram is bidirectional depending upon the input voltage behaviour i.e. increasing or decreasing from the expected output voltage.

When v_s is less than required v_L, the power converter produce a voltage across the transformer in a direction such that this voltage adds to the input voltage to get desired output voltage (i.e. the current flows from the input side to the output side through rectifier and inverter path). When v_s is more than desired v_L, the power converter produces a voltage in a direction such that this voltage is subtracted from the input voltage to get desired output voltage (i.e. the current flows from the output side to the input side through inverter and rectifier path).

A. Energy Unit

The energy unit in SVR plays the important role of providing the sufficient amount of energy so that the load voltage will be in the acceptable limits. The different types of energy storage units are energy supply using Non-Controlled rectifier, energy supply using Controlled Rectifier, Accumulator cell etc. In case of Non-Controlled rectifier only one way current flow is possible, so this problem is solved by using Controlled Rectifier. Nowadays Controlled Rectifier strategy is most popular because of its ability to remove harmonics since it acts as active filter and can provide unity Power factor correction.

B. Inverter

The inverter is used to produce required output voltage by using the DC voltage provided by Energy storage unit. The different Inverter structures are semi-bridge, full-bridge and push-pull Inverter. Full-bridge Inverter is most commonly used because it is easy to implement and removes the problem of zero vector switching which is important in three phase systems but it suffers from the bridge-arm shoot-through problem. In push-pull inverter structure in each of the three arms, only one semiconductor/switching device is on at any given time, so this structure eliminates the problem of bridge-arm shoot-through.

C. Filter

Semiconductor devices like IGBTs, MOSFETs etc. are used as switching devices in rectifier and inverter part. Since these devices are having nonlinear characteristic, they produce high frequency harmonics which is undesirable in case of complex loads. To solve this problem filter is required which can be placed before or after buck-boost transformer. The rating of the filter is decided by the requirement of output load voltage and available input voltage range.

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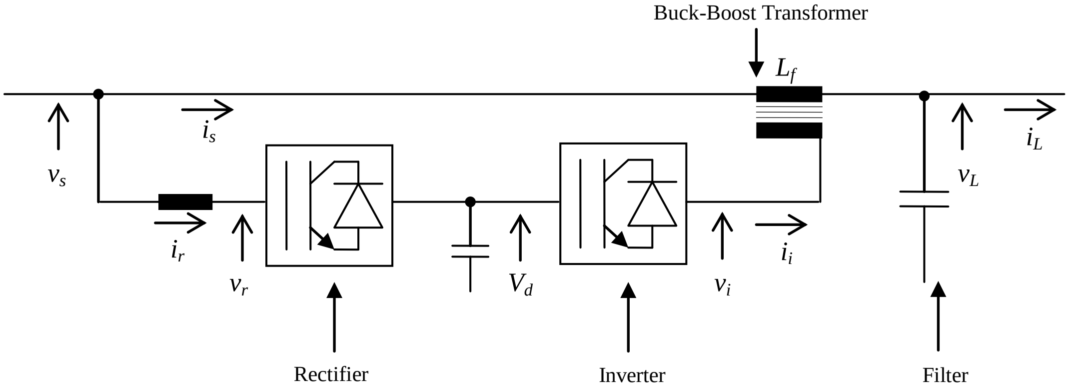

Fig. 1 Simplified Block Diagram of Static Voltage Regulator

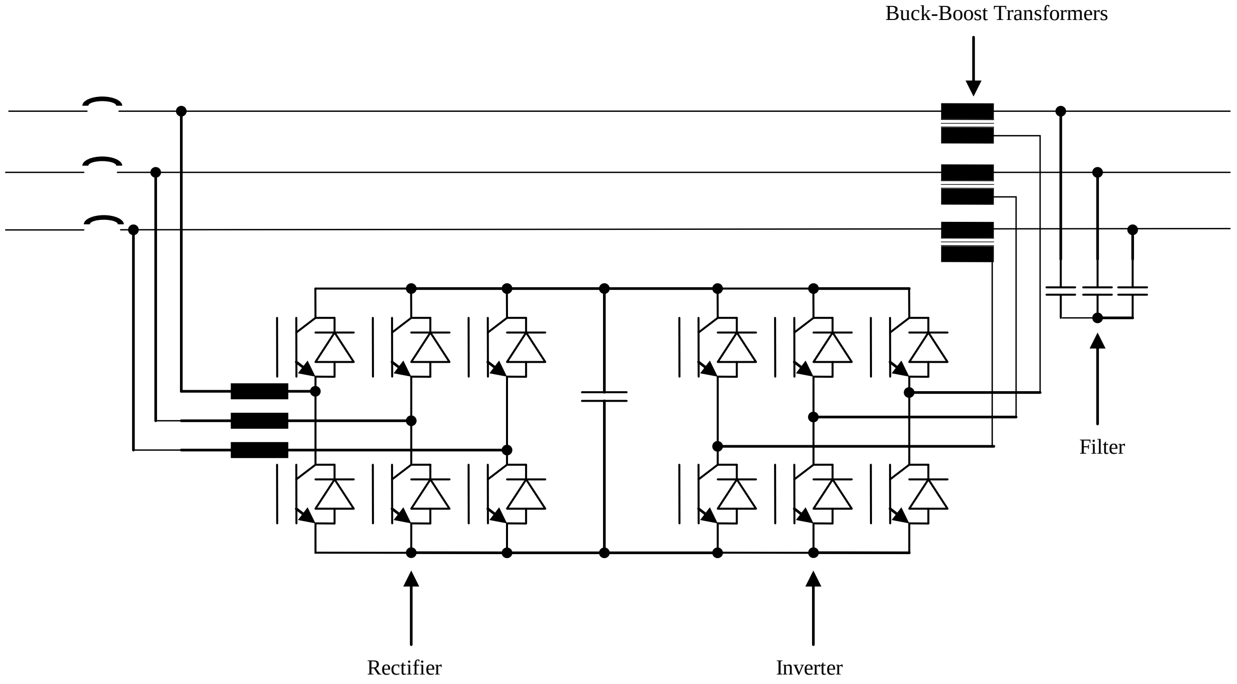

Fig. 2 Detailed Block Diagram of Static Voltage Regulator

D. Buck-Boost Transformer

Three single phase transformers are used for buck-boost purpose depending on the supply voltage. The transformer rating i.e. turns ratio design is important because the current direction is bidirectional.

III. PROPOSED CONTROL SCHEME

A. Proposed PI Controller

The PI controller equation in time domain is:

$$u = K_p e + K_I \int e \, dt \tag{1}$$

Where e is the error of the quantity to be controlled, u the output of the controller applied to the plant. K_p is the proportional gain and K_I is the integral gain.
This can be written in discrete form as:

$$u_k = K_p e_k + K_I \sum \left(e_j + e_{j-1}\right) \Delta T / 2$$

→ from $j = 1$ to k (2)

Where ΔT is the sampling time. Similarly, for the previous sample,

$$u_{k-1} = K_p e_{k-1} + K_I \sum \left(e_j + e_{j-1}\right) \Delta T / 2$$

→ from $j = 1$ to $k-1$ (3)

Subtracting, we get:

$$u_k = u_{k-1} + K_p \left(e_k - e_{k-1}\right) + K_I \left(e_k + e_{k-1}\right) \Delta T / 2 \tag{4}$$

For all PI controllers, the above equation can be used by using proper parameters. K_p and K_I would be different for different controllers.

B. Proposed Rectifier Control

The proposed rectifier control is shown in the Fig. 3.
In the Rectifier control the parameters to be sensed are v_s, i_r and v_d. v_s, i_r each has three phases, so total parameters are 7.

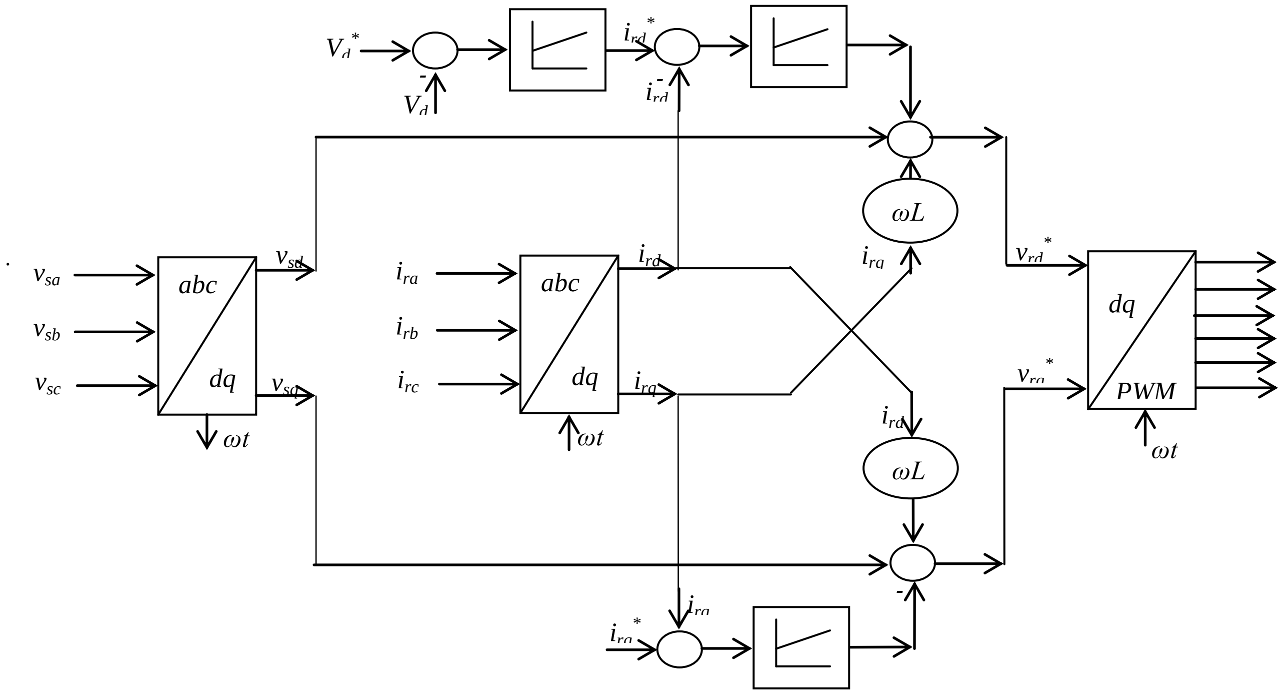

Fig. 3 Block Diagram of Three Phase Rectifier Controller

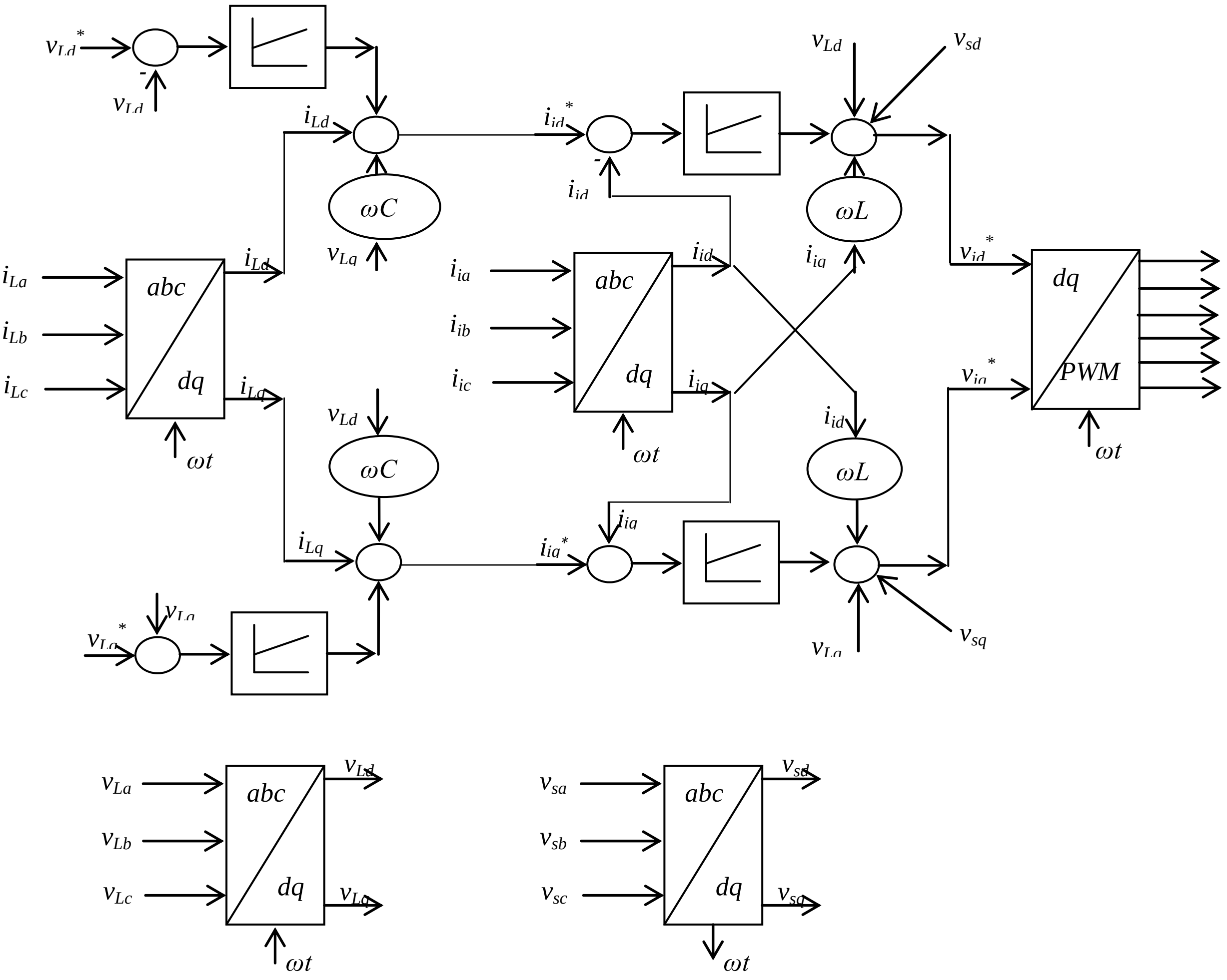

Fig. 4 Block diagram of Three Phase Inverter Controller

By using these parameters control pulses i.e. PWM signals are generated for the switching of the semiconductor devices like IGBT. The duty cycle of the PWM pulses are adjusted according to the parameter variations.

Referring to the block diagram given in Fig. 3, the control Equations for Rectifier can be written as:

$$\begin{aligned}
&i_{rd\,k}^{*} = i_{rd\,k-1}^{*} + K_{pVd}\left(e_{Vdk} - e_{Vdk-1}\right) + K_{IVd}\left(e_{Vdk} + e_{Vdk-1}\right)\Delta T/2 \\
&i_{rq\,k}^{*} = 0 \\
&u_{irdk} = u_{irdk-1} + K_{pir}\left(e_{irdk} - e_{irdk-1}\right) + K_{Iir}\left(e_{irdk} + e_{irdk-1}\right)\Delta T/2 \\
&v_{rd\,k}^{*} = v_{sd} - u_{irdk} + \omega L_r i_{rq} \\
&u_{irqk} = u_{irqk-1} + K_{pir}\left(e_{irqk} - e_{irqk-1}\right) + K_{Iir}\left(e_{irqk} + e_{irqk-1}\right)\Delta T/2 \\
&v_{rq\,k}^{*} = v_{sq} - u_{irqk} - \omega L_r i_{rd}
\end{aligned} \tag{5}$$

K_{pVd} would be near to $C_d / \Delta T$, where C_d is the DC Capacitance value. Similarly, K_{pir} would be near to $L_r / \Delta T$. K_I values are to be adjusted for stability.

C. Proposed Inverter Control

In the Inverter control the parameters to be sensed are v_L, v_s, i_L and i_i. The proposed Inverter control is shown in the Fig. 4. Referring to the block diagram given in Fig. 4 below, the control equations for the Inverter can be written as:

$$\begin{aligned}
&u_{VLdk} = u_{VLdk\,-1} + K_{pVL}\left(e_{vLdk} - e_{vLdk-1}\right) + K_{IvL}\left(e_{vLdk} + e_{vLdk-1}\right)\Delta T/2 \\
&i_{id\,k}^{*} = n\left(i_{Ld} + u_{VLdk} - \omega C_f v_{Lq}\right) \\
&u_{VLqk} = u_{VLdk\,-1} + K_{pVL}\left(e_{vLqk} - e_{vLqk-1}\right) + K_{IvL}\left(e_{vLqk} + e_{vLqk-1}\right)\Delta T/2 \\
&i_{iq\,k}^{*} = n\left(i_{Lq} + u_{VLqk} + \omega C_f v_{Ld}\right) \\
&u_{iidk} = u_{iidk\,-1} + K_{pii}\left(e_{iidk} - e_{iidk-1}\right) + K_{Iii}\left(e_{iidk} + e_{iidk-1}\right)\Delta T/2 \\
&v_{id\,k}^{*} = \left(v_{Ld} - v_{sd}\right)/n + u_{iidk} - \omega L_f i_{iq} / n^2 \\
&u_{iiqk} = u_{iiqk\,-1} + K_{pii}\left(e_{iiqk} - e_{iiqk-1}\right) + K_{Iii}\left(e_{iiqk} + e_{iiqk-1}\right)\Delta T/2 \\
&v_{iq\,k}^{*} = \left(v_{Lq} - v_{sq}\right)/n + u_{iiqk} + \omega L_f i_{id} / n^2
\end{aligned} \tag{6}$$

IV. SPACE VECTOR MODULATION

Space Vector Pulse Width Modulation (SVPWM) is controlling method for changing the width of the pulses applied to switching devices according to the different parameter variations. It is used for the generation of alternating current (AC) waveforms. It is most commonly used in three phase AC motor drives by using DC voltage because it has a higher DC-side voltage utility efficiency as compared to sine pulse width modulation (SPWM). The important thing in SVPWM is calculation of the duty cycle of pulses applied to power switches in Rectifier and Inverter parts, as well as decision of the position of vector in different segments and pulse sequence in each switching cycle.

A three-phase inverter as shown in the Fig. 5 converts a DC voltage which is generated by using different energy storage units as mentioned in section II, using six switches to three output arms which are connected to a three-phase AC motor drives. The switches are controlled in such a way that at any given time only one switch in each arm is on so that DC voltage will not get shorted. This is achieved by the complementary operation of the switches within the arm. i.e. if A is on then D is off and vice versa. This results in eight possible switching vectors for the inverter, six active switching vectors and two zero vectors. This is shown in the Table 1.

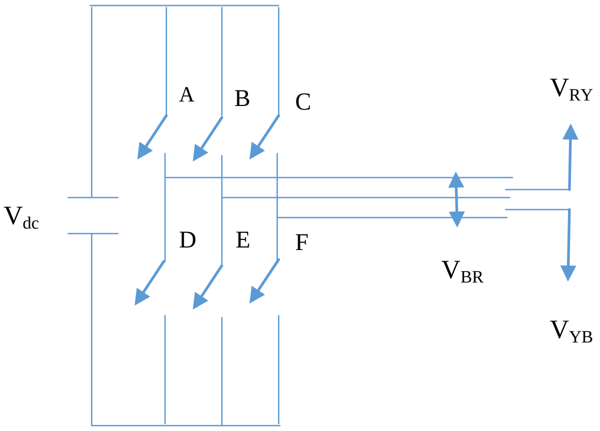

Fig. 5 Three Phase Inverter

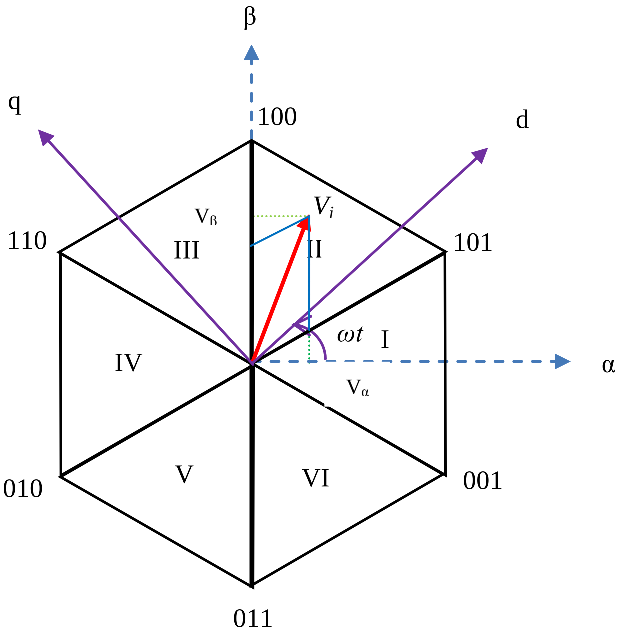

Fig. 6 Space Vector Hexagon with α-β and d-q axes

The Space Vector Hexagon of a two-level Inverter is shown in Fig.6. The number in roman digits is the number of the segment. For example, segment I is from $-\pi/6$ to $\pi/6$ segment II is from $\pi/6$ to $\pi/2$, etc. After getting direct and quadrature components for rectifier and inverter, vectors V_α, V_β are calculated for generation of the PWM pulses. From Fig. 7 the equations for V_α and V_β are as follows:

$$\begin{aligned}
V_\alpha &= V_d * \cos(\omega * t) - V_q * \sin(\omega * t) \\
V_\beta &= V_d * \sin(\omega * t) - V_q * \cos(\omega * t)
\end{aligned} \tag{7}$$

Based on the values of V_α, V_β, location of the vector i.e. segment is decided and according to that times t_1, t_2 and t_0 are calculated. To reduce the switching frequency of devices,

Table 1: Different Vectors and Corresponding status of Switches (MOSFETs/IGBTs)

Vector	**A**	**B**	**C**	**D**	**E**	**F**	V_{RY}	V_{YB}	V_{BR}	
000	OFF	OFF	OFF	ON	ON	ON	0	0	0	Zero Vector
001	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	Active Vector
101	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	Active Vector
100	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	Active Vector
110	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	Active Vector
010	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	Active Vector
011	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	Active Vector
111	ON	ON	ON	OFF	OFF	OFF	0	0	0	Zero Vector

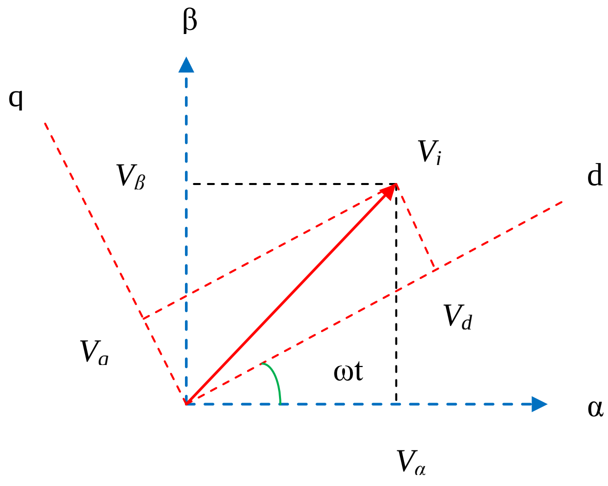

Fig. 7 Calculation of V_α, V_β vectors from α-β and d-q axes

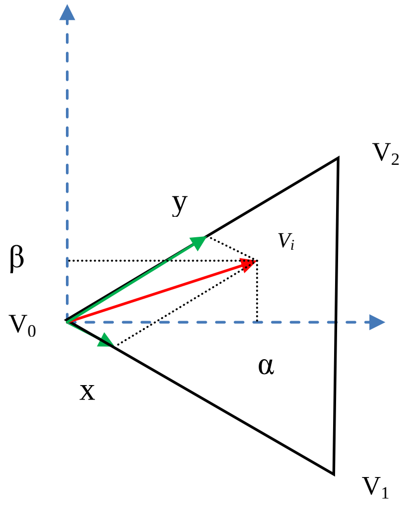

Fig. 8 Calculation of Vector lengths x and y

V_0 is produced by both (*000*) and (*111*) alternately. An example of Segment # I is shown below.

001-101-111-101-001-000-001- etc.
It should be noted that the periods also would be t_1-t_2-t_0-t_2-t_1-t_0-t_1-t_2-t_0- etc.

The different segments shall be as follows:

$V_\alpha \geq 0$ → Segments VI, I, II

$V_\beta < 0 \text{ and } \left(-V_\beta\right) > V_\alpha / \sqrt{3}$ → Segments VI

$V_\beta \geq 0 \text{ and } V_\beta > (V_\alpha / \sqrt{3})$ → Segments II

Otherwise → Segments I

$V_\alpha < 0$ → Segments III, IV, V

$V_\beta \geq 0 \text{ and } V_\beta > (-V_\alpha / \sqrt{3})$ → Segments III

$V_\beta < 0 \text{ and } \left(-V_\beta\right) > -V_\alpha / \sqrt{3}$ → Segments V

Otherwise → Segments IV

The vector lengths x and y in particular segment are calculated as follows:

Consider Segment I as shown in the Fig. 8

$$\begin{aligned} V_\alpha &= x * \cos(\pi/6) + y * \cos(\pi/6) \\ &= 0.866 * (x+y) \\ V_\beta &= -x * \sin(\pi/6) + y * \sin(\pi/6) \\ &= (-x+y)/2 \\ x &= V_\alpha / 1.732 - V_\beta \\ y &= V_\alpha / 1.732 + V_\beta \end{aligned} \qquad (8)$$

Similarly for Segment II,

$$\begin{aligned} x &= V_\alpha / 0.866 \\ y &= V_\beta - x/2 \end{aligned} \qquad (9)$$

For Segment III,

$$\begin{aligned} y &= -V_\alpha / 0.866 \\ x &= V_\beta - y/2 \end{aligned} \qquad (10)$$

For Segment IV,

$$\begin{aligned} x &= -V_\alpha / 1.732 - V_\beta \\ y &= -V_\alpha / 1.732 + V_\beta \end{aligned} \tag{11}$$

For Segment V,

$$\begin{aligned} x &= -V_\alpha / 0.866 \\ y &= -V_\beta - x/2 \end{aligned} \tag{12}$$

For Segment VI,

$$\begin{aligned} y &= V_\alpha / 0.866 \\ x &= -V_\beta - y/2 \end{aligned} \tag{13}$$

From the values of x and y we will calculate times t_1, t_2 and t_0

$$\begin{aligned} t_1 &= x \text{ or } y; \\ t_2 &= x \text{ or } y \\ t_0 &= t_s - t_1 + t_2 \end{aligned} \tag{14}$$

The values of t_1 and t_2 can be either x or y depending on the trace of the segment i.e. clockwise or anticlockwise direction. t_s is the sampling period/time.

V. EXPERIMENTAL RESULTS

Fig. 9(a) and 9(b) show the Ideal Space Vector Pulse Width Modulated Waveform of R-Phase and Y-Phase respectively at the output of Rectifier and Inverter. Here in order to compare the pulse widths of ideal and practical waveforms for R and Y phases clearly, we have taken less number of samples (18) per complete cycle i.e. 360^0. In practical case we have taken 200 samples per cycle and sampling period is 100 microseconds. So total time for 200 samples is 20 milliseconds i.e. the frequency is 50Hertz.

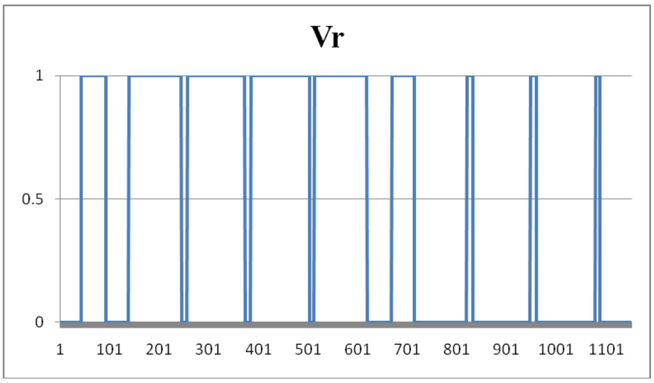

Fig. 9(a) Ideal SVPWM Waveform of R-Phase at Inverter and Rectifier Output

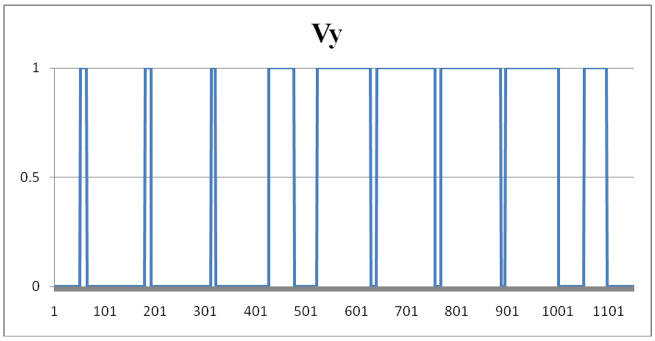

Fig. 9(b) Ideal SVPWM Waveform of Y-Phase at Inverter and Rectifier Output

Fig. 9(c) shows ideal line to line voltage waveform between R and Y phases for 18 samples per cycle. In Fig. 9(d) and 9(e) red coloured waveform gives the R to Y voltage waveform at Rectifier and Inverter output respectively.

By comparing these two waveforms with the ideal one as in the Fig.9(c), it is clear that the result we obtained matches almost closely to the ideal one. Fig. 9(f) shows R-Y voltage at the output of Inverter (after filter) and Fig. 9(g) shows R,Y, B voltages given to the load. Different AC voltages i.e. Y-B and B-Y are also obtained by using proper filters.

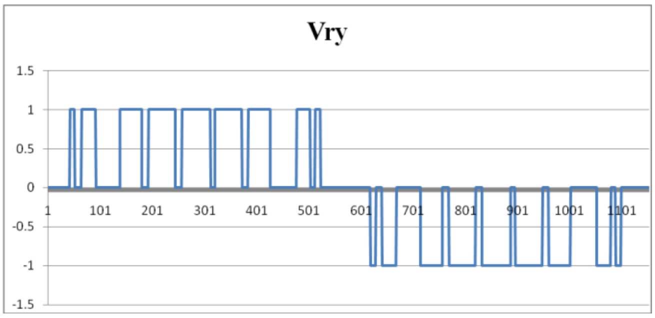

Fig. 9(c) Ideal SVPWM Waveform of R-Y Voltage at Inverter and Rectifier Output

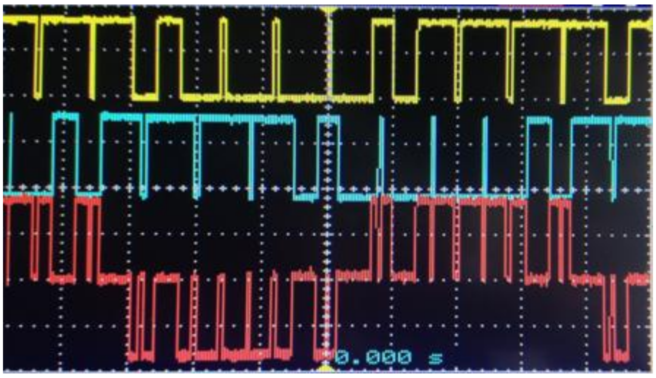

Fig. 9(d) Practical SVPWM Waveform of R-Y Voltage at Rectifier Output

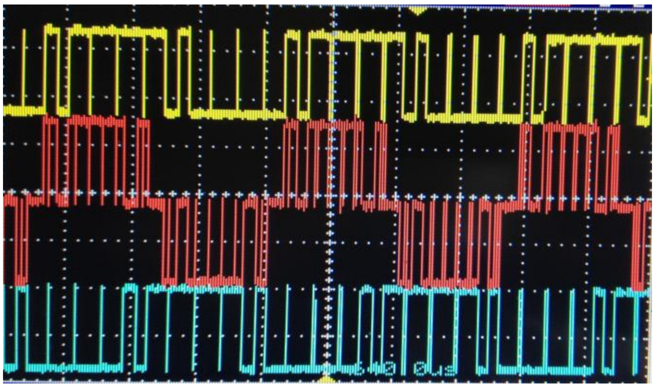

Fig. 9(e) Practical SVPWM Waveform of R-Y Voltage at Inverter Output

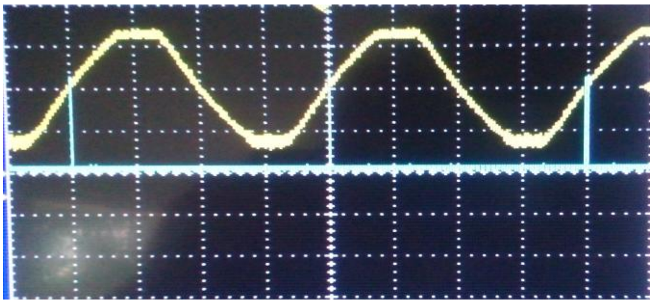

Fig. 9(f) R-Y Voltage at Invertre Output (after filter) given to the load

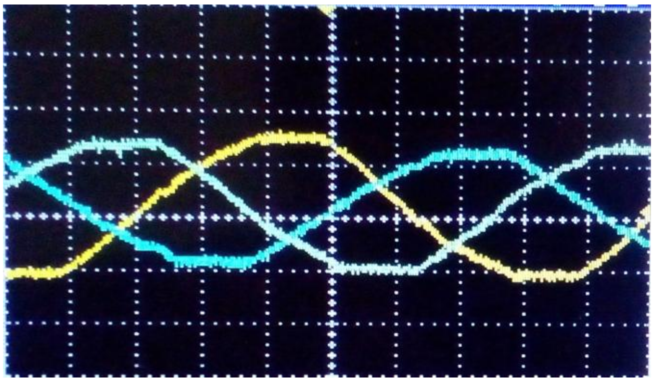

Fig. 9(g) R, Y and B Voltages at Invertre Output (after filter) given to the load

VI. CONCLUSION

Firing pulses i.e. PWM signals for switching of MOSFETs/IGBTs are generated successfully using Space Vector Pulse Width Modulation technique which is the most efficient method of control in three phase static voltage regulator today, since ideal and practical results are very closely matched. The proposed control scheme requires less computation time, so by using high performance microcontrollers/microprocessors it is possible to process on more number of samples per cycle in order to remove the harmonics and to obtain the higher efficiency.

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