DESIGN AND IMPLEMENTATION OF VARIABLE HYSTERESIS BAND VOLTAGE CONTROLLER BASED DVR

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Abstract: This paper deals with the design and implementation of variable hysteresis band voltage controller based dynamic voltage restorer (DVR). The aim of variable hysteresis band voltage controller is overcomes the major drawbacks in fixed hysteresis band voltage controller i.e., uneven stress on switches due to large ripples in filter currents and variation in switching frequency can be eliminated by using variable hysteresis band control scheme. The performance of the variable hysteresis band voltage controller based DVR depends on the values of system parameters and components and injects appropriate compensated voltages into the system and regulates the load voltages. The DVR is to mitigate all typical voltage related problems at the distribution system load center like voltage sag, voltage swell, voltage harmonics and interruptions etc. The compensation capability of this proposed topology is analyzed based on simulation studies and corresponding results are compared with different switching control strategies.

Index Terms: Power Quality (PQ), Fixed Hysteresis Band Controller (FHBC), Variable hysteresis band Controller (VHBC), Dynamic Voltage Restorer (DVR)

I. INTRODUCTION

Now a day, power quality is the major concern in power system network. The wide usage of modern power electronic equipments, frequent starting and stop of induction dives and integration of renewable energy sources etc. causes power quality (PQ) problems[1]-[6]. The well-known power quality issues are voltage sag/swell, harmonic content in voltage and current and so on. To mitigate these PQ issues custom power devices (CPDs) are used [7]-[9]. In distribution grid these CPDs can be connected in series or in parallel or combination of both at the point of common coupling (PCC). Dynamic voltage restorer (DVR) is one of the series connected type CPD.DVR consists of voltage source inverter (VSI) connected between load and PCC through coupling transformer and interface filter. Hence the DVR injects a set of controllable three-phase ac voltages in series and synchronism with the distribution feeder voltages such that the load-side voltage is restored to the desired amplitude and waveform even when the source voltage is unbalanced or distorted. In this paper primary aspect is the design of DVR for the selection of suitable VSI topology based on the nature of load and network configuration. Three phase neutral clamped VSI topology is shown in Fig.1 is used. It consists of six power semiconductor switches each with an anti-parallel diode and two identical DC storage capacitors. This topology enables the independent control of each leg of the series inverters, but it requires capacitor voltage balancing [10]. In [11]-[13], four-leg VSI topology for series active filter has been proposed for a three-phase four-wire system. This topology avoids the voltage balancing of the capacitor, but the independent control of the inverter legs is not possible. To overcome the problems associated with the four-leg topology, this topology is equipped to compensate DC components of load also, but due to the presence of DC component in VSI, the two DC capacitors are charged to different voltages. The total voltages of DC capacitors are however maintained at a constant value using a DC voltage control loop. Hence, with the presence of DC component in load, an extra circuitry and appropriate changes in control are required to maintain individual DC voltages at constant value. Hence this VSI topology inverters which work independently and they work on the output feedback of variable hysteresis band voltage control. The variable hysteresis band voltage control generates reference injected voltage signals with influence of system parameters and to generate switching signals to the converter with proper switching times. Such that the accurate tracing bus voltages can be present as per requirement. The VSC are formed by the combination of reactor (L_{se}), resistor (R_{se}), ac filter capacitors (C_{se}) and three phase converters to prevent the flow of the power quality problems into the distribution system generated due to switching at each phase of PCC. Regulate the load voltages by DVR against voltage sags, swells etc. The second aspect is the design of DVR for the selection of suitable coupling transformer, it can experience saturation during the transient period after a voltage sag starts. For preventing this, normally a rating flux that is double of the steady-state limit is chosen. An alternative method for preventing the coupling transformer saturation based on limiting the flux-linkage during the transient switch-on period is proposed in [14] -[15]. The DVR coupling transformer performs two important functions: voltage boost and electrical isolation. Simulations on a power distribution system are carried out and results are presented.

II. SYSTEM REPRESENTATION

Schematic diagram of a conventional three phase three leg-four wire DVR topology is shown Fig.1 This topology consists of voltage source inverter (VSI) connected in series to load at the PCC through coupling transformer, interface filter (interface inductor (L_{se}) and capacitor (C_{se})). The purpose of interfacing filter is to shape inject voltages while tracking the reference injected voltages. Here v_{la}, v_{lb}, v_{lc} represents the instantaneous phase voltages at the PCC, which may be distorted because of faults that can exist in the system are single line-to-ground fault, double line-to-ground, line-to-line fault and three-phase fault. The injected voltages v_{inja}, v_{injb}, v_{injc} represents the actual injected voltages obtained using hysteresis current control techniques i_{sa}, i_{sb}, i_{sc} represents the source currents and i_{la}, i_{lb}, i_{lc} represents the load currents. The capacitance C_{dc} is the dc storage capacitor used for maintaining the input voltage of VSI at reference value of V_{dcref}. However, instantaneous voltage across C_{dc} is denoted as v_{dc} in following text.

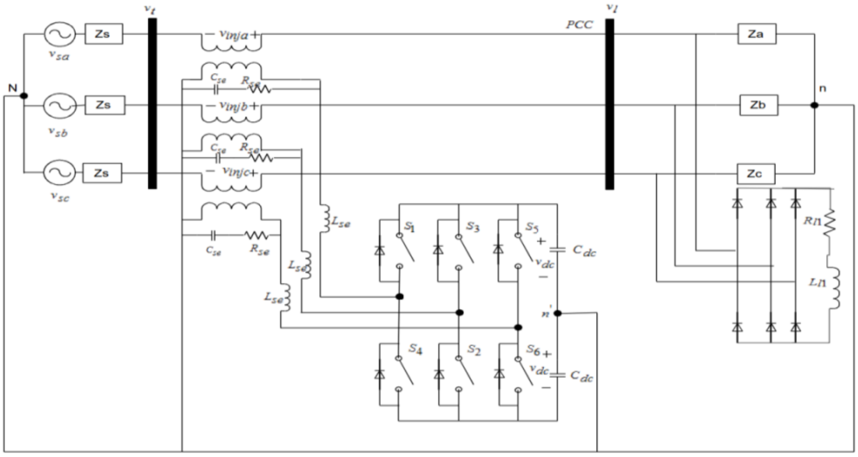

Fig.1 Three-phase three Leg-Four Wire DVR topology

III. SWITCHING CONTROL TECHNIQUES

For switching of the VSI in DVR the various control techniques available in the literature like hysteresis current and adaptive voltage control techniques are discussed in this section. In actual distribution system the DVR consists a voltage source inverter which realize the reference injected voltages and this VSI is controlled by using a suitable switching techniques like the fixed hysteresis voltage band controller technique and variable hysteresis voltage band controller technique.

3.1 Fixed hysteresis band voltage controller

The principle diagram of fixed hysteresis band voltage control is shown in Fig.2, the hysteresis value band governs the inverter switching pattern in such a manner as to maintain the mean value of the control state at the required value. The instantaneous value of the output voltage is compared with the reference voltage, at the point when the sensed output signal strays from the reference by more than a prescribed value, the inverter is worked to diminish the deviation. This implies that switching happens at whatever points the output current crosses the values of HB. Where HB is the width of the hysteresis band. The switching commands or the VSI top switches are issued whenever the error signal (e_f) between reference (v^*_{inj}) and actual (v_{inj}) injected voltages exceeds a specified tolerance hysteresis band 'h'. The schematic of fixed hysteresis current control scheme is illustrated in Fig. The complementary commands (S'_4 , S'_6 , S'_2) are issued to the bottom switches and are not shown for simplicity. Thus the actual injected voltage waveforms are restricted to flow with in a channel of width (HB) that follows the reference injected voltage waveform. The frequency of inverter depends of the hysteresis band. The output voltage will contain significant ripples due to inductance trapped energy that prolongs the charging and discharging of the capacitor. To solve this problem, it is necessary to improve the hysteresis control.

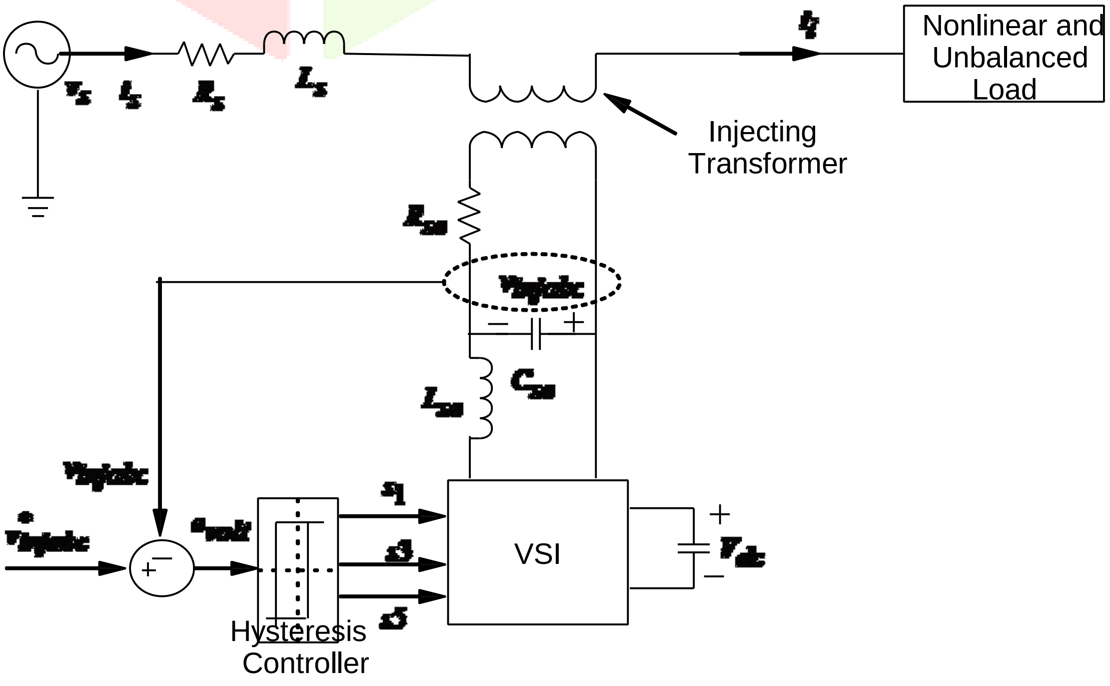

Fig.2 Single line diagram of fixed hysteresis band voltage control based DVR

3.2 Variable hysteresis band voltage controller

The fixed hysteresis band is very simple and easy to implement, but it has the disadvantages of uncontrollable high switching frequency. This high frequency produces a great stress on the power transistor and induces important switching losses. An adaptive hysteresis band method allows operation at nearly constant frequency and is usually performed by software which uses the system parameters. The block diagram of a variable hysteresis band voltage control is shown in Fig.3. The actual injected voltages (v_{inj}) are compared with reference injected voltages (v_{inj}^*) to generate the error signal (e_f). The instantaneous values of the system parameters (PCC voltages, DC link voltage, reference injected voltages, filter capacitor and interfacing inductance) are measured and the hysteresis band *h* is calculated by the band calculator block for a specified switching frequency. The hysteresis controller based on the error signal and the computed hysteresis band issues the switching commands for the inverter.

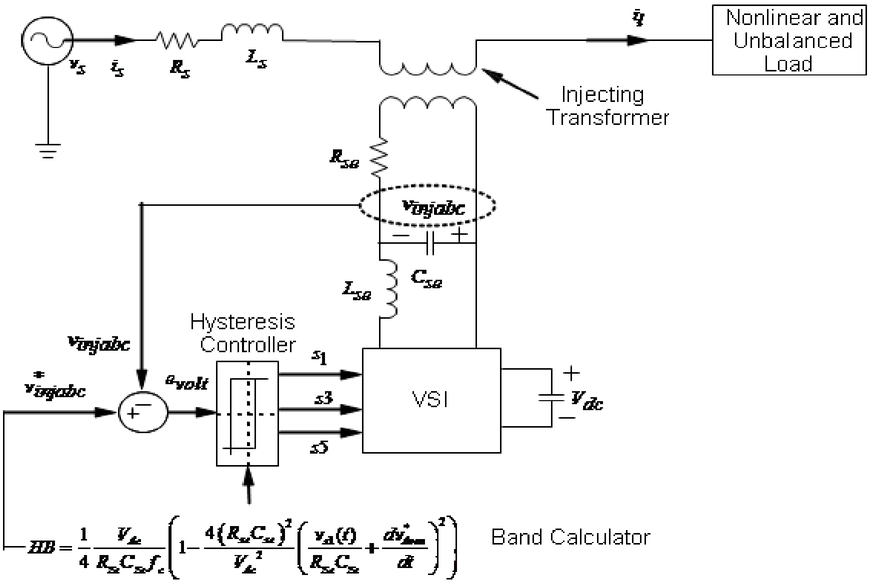

Fig.3 Single line diagram of variable hysteresis band voltage control based DVR

3.3 Selection of Hysteresis Band

In this section proposes the selection of the hysteresis band (*h*) value, in fixed hysteresis band controller the *h* value is 10% of the compensated current, but it has the disadvantages of uncontrollable high switching frequency. This high frequency produces a great stress on the power transistor and induces important switching losses. The modified switching hysteresis band controller method, the selection of *h* value depend of the system parameters. Hence this *h* value allows operation at nearly constant switching frequency and reduce stress on the power transistor and switching losses. The DVR filter band controller system has been applying KVL and KCL given circuit as shown in Fig.3.

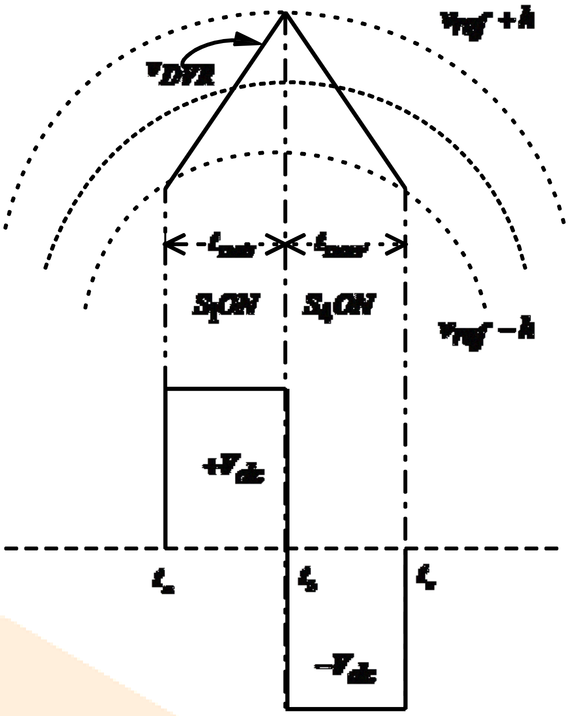

Fig.4 switching operation of band controller

$$\frac{dv_{dvr}}{dt}=\frac{1}{C_{se}}\left(I_{inv}-I_L\right) \tag{1}$$

Where v_{dvr} is the inverter-side voltage and to having paid attention to Fig.4, the relations can be obtained.

$$v_{dvr}=-v_{inv}+L_{se}C_{se}\frac{dv_{dvr}^2}{dt}+R_{se}C_{se}\frac{dv_{dvr}}{dt}-L_{se}\left(\frac{di_L}{dt}\right)-R_{se}i_L \tag{2}$$

From the geometry of Fig.4, the following equations can be written in the hysterersis-band curvature with respective switching intervals

$$\frac{dv_{dvra}^{+}}{dt}t_{12ON}-\frac{dv_{dvra}^{*}}{dt}t_{12ON}=2HB \tag{3}$$

$$\frac{dv_{dvra}^{-}}{dt}t_{12OFF}-\frac{dv_{dvra}^{*}}{dt}t_{12OFF}=-2HB \tag{4}$$

$$t_{12ON}+t_{12OFF}=T_{sw}=\frac{1}{f_{sw}} \tag{5}$$

Where t_{12ON} and t_{12OFF} are the respective switching intervals, and f_{sw} is the switching frequency. Adding equation (3) and (4)

$$\frac{dv_{dvra}^{+}}{dt}t_{12ON}+\frac{dv_{dvra}^{-}}{dt}t_{12OFF}-\frac{dv_{dvra}^{*}}{dt}(t_{12ON}+t_{12OFF})=0 \tag{6}$$

$$\frac{dv_{dvra}^{+}}{dt}=\frac{V_{dc}-v_{s1}(\mathrm{t})}{R_{se}C_{se}} \tag{7}$$

$$\frac{dv_{dvra}^{-}}{dt}=\frac{V_{dc}+v_{s1}(\mathrm{t})}{R_{se}C_{se}} \tag{8}$$

$$where, v_{s1}(\mathrm{t})=v_{ref}+L_{se}C_{se}\frac{dv_{ref}^2}{dt^2}+R_{se}C_{se}\frac{dv_{ref}}{dt}$$

Substituing dv^{+}_{dvra}/dt and dv^{-}_{dvra}/dt values in the equation (7)

$$\left(\frac{V_{dc}-v_{s1}(\mathrm{t})}{R_{se}C_{se}}\right)t_1+\left(\frac{V_{dc}+v_{s1}(\mathrm{t})}{R_{se}C_{se}}\right)t_2-\frac{dv^{*}_{dvra}}{dt}(t_1+t_2)=0 \qquad (9)$$

Simplify and substituting $(t_1+t_2)=1/f_c$ in the equation (9)

$$(t_1-t_2)=\frac{R_{se}C_{se}}{V_{dc}\,f_c}\left(\frac{v_s(t)}{R_{se}C_{se}}+\frac{dv^{*}_{dvra}}{dt}\right) \qquad (10)$$

Substrating (3) from (4), we get

$$\frac{dv^{+}_{dvra}}{dt}t_1-\frac{dv^{-}_{dvra}}{dt}t_2-\frac{dv^{*}_{dvra}}{dt}(t_1-t_2)=4HB \qquad (11)$$

Substituing dv^{+}_{dvra}/dt and dv^{-}_{dvra}/dt values in the equation (11)

$$\left(\frac{V_{dc}-v_{s1}(\mathrm{t})}{R_{se}C_{se}}\right)t_1-\left(\frac{V_{dc}+v_{s1}(\mathrm{t})}{R_{se}C_{se}}\right)t_2-\frac{dv^{*}_{dvra}}{dt}(t_1-t_2)=4HB \qquad (12)$$

Simplify and substituting $(t_1+t_2)=1/f_c$ in the equation (12)

$$\frac{V_{dc}}{R_{Se}C_{Se}}(t_1+t_2)-\frac{v_{s1}(t)}{R_{Se}C_{Se}}(t_1-t_2)-\frac{dv^{*}_{dvra}}{dt}(t_1-t_2)=4HB \qquad (13)$$

$$\frac{V_{dc}}{R_{Se}C_{Se}}(t_1+t_2)-(t_1-t_2)\left(\frac{v_{s1}(t)}{R_{Se}C_{Se}}+\frac{dv^{*}_{dvra}}{dt}\right)=4HB \qquad (14)$$

Here substituing (t_1+t_2) and (t_1-t_2) value in equation (13)

$$\frac{V_{dc}}{R_{Se}C_{Se}\,f_c}-\frac{R_{se}C_{se}}{V_{dc}\,f_c}\left(\frac{v_{s1}(t)}{R_{Se}C_{Se}}+\frac{dv^{*}_{dvra}}{dt}\right)^2=4HB \qquad (15)$$

$$HB=\frac{1}{4}\frac{V_{dc}}{R_{Se}C_{Se}\,f_c}\left(1-\frac{4(R_{se}C_{se})^2}{V_{dc}^{\ 2}}\left(\frac{v_{s1}(t)}{R_{Se}C_{Se}}+\frac{dv^{*}_{dvra}}{dt}\right)^2\right) \qquad (16)$$

Here, V_{dc} is the dc-link capacitor voltage, dv^{*}_{dvra}/dt is the slope of the reference voltages signlas. The hystersis band HB can be modulated at different points of fundamental frequency to control the switching pluses of the inveter. The calculaed hysteresis band width HB is applied to the switching operation of hystersis controller as shown in Fig.3.

IV. SIMULATION STUDIES

The extensive case study of DVR proposed topologies, were obtained through simulation using SIMULINK/MATLAB environment.

TABLE I. SYSTEM PARAMETERS

Line-Voltage (V_{sa})	3-pahse 50HZ, 200 Volts
Feeder Impendence	1+3.14Ω
Series LC Filter -(L_{Se}) & (C_{se})	2.3mh & 80µF
Filter-Resistance (R_{se})	0.1Ω
Unbalanced Load	50+j31.4Ω,75+j31.4Ω and 100+j15.7Ω
Nonlinear Load	Three phase Diode with R-L load 300Ω and 50mh
Dc side capacitor (Cdc) & capacitor Voltage(V_{dc})	2000µF , 1040 V
V_{dcref}	1040
Three phase-Linear Transformer	4kva,230/230,50hz, 0.002pu,0.008p.u 1:1 ratio
Switching frequency(f_c)	10khz

The system parameters which are given Table I. The simulation results for both the hysteresis voltage controlled topology are presented in this section for better understanding and comparison between both the topologies.

4.1 Case-1: Using fixed hysteresis voltage Controller

In this case it is assumed steady state condition the simulation time is taken as t=0 to t=0.08 sec with constant nonlinear load and unbalanced load. In case 1 applied a 44% of sag was considered in all phases of the terminal at the time of interval 0.02s to 0.04s and applied fixed hysteresis band voltage controller. The supply voltages and load voltages with 4.96% total harmonic distortions before compensation are same shown in Fig. 5(a). Now to compensate the load voltages with help of DVR. Initially before compensation to generate the accurate reference voltages (V_{dvr}^{*}) are shown in fig 5(b). The Instantaneous DVR injected voltages (V_{dvrinj}) are compared with reference DVR voltages (V_{dvr}^{*}) with fixed hysteresis band (HB=±6.5) value. At this point when the sensed output signal strays from the reference by more than a prescribed value, the inverter is worked to diminish the deviation. Hence the VSC injected the accurate injected voltages with minimum phase jump angle, and compensate load voltages becomes pure sinusoidal is shown fig.5(c) with 0.77% total harmonic distortions. After compensation active power also compensated during the sag intervals of time is shown in fig.5(e). The main drawback of the fixed hysteresis voltage Controller is output current having small ripples due to constant hysteresis band, switching losses at converter are more and error between reference DVR voltages (V_{dvr}^{*}) and The Instantaneous DVR injected voltages (V_{dvrinj}) are more is shown fig.5(d), now to reduce these drawbacks with help of adaptive Hysteresis voltage controller.

4.2 Case2: DVR topology with adaptive hysteresis voltage Controller

In case 2 applied a 25% of swell was considered in all phases of the terminal at the time of interval 0.02s to 0.04s and applied adaptive hysteresis voltage controller.In adaptive hysteresis voltage controller the HB value can calculate at nearly constant switching frequency and is usually performed by software which uses the system parameters by using equation (16). The modified The Instantaneous DVR injected voltages (V_{inj}) are compared with reference DVR voltages (V_{dvr}^{*}) at instantaneous hysteresis band (HB) with each sample time and constant switching frequency (f_c) technique.

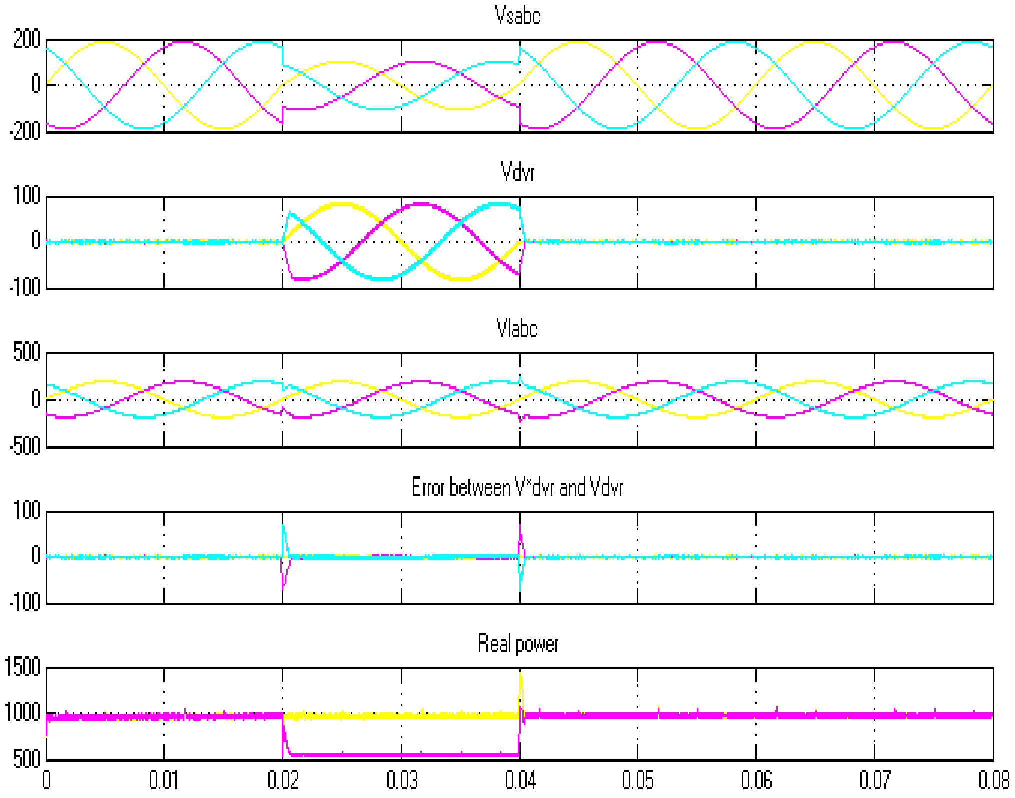

Fig.5 (a) Source voltages (V_{sabc}),5(b) Injected voltages (V_{dvrinj}), 5(c) Load voltages (V_{labc}), 5(d) error between reference injected voltages and actual injected voltages and 5(e) real power

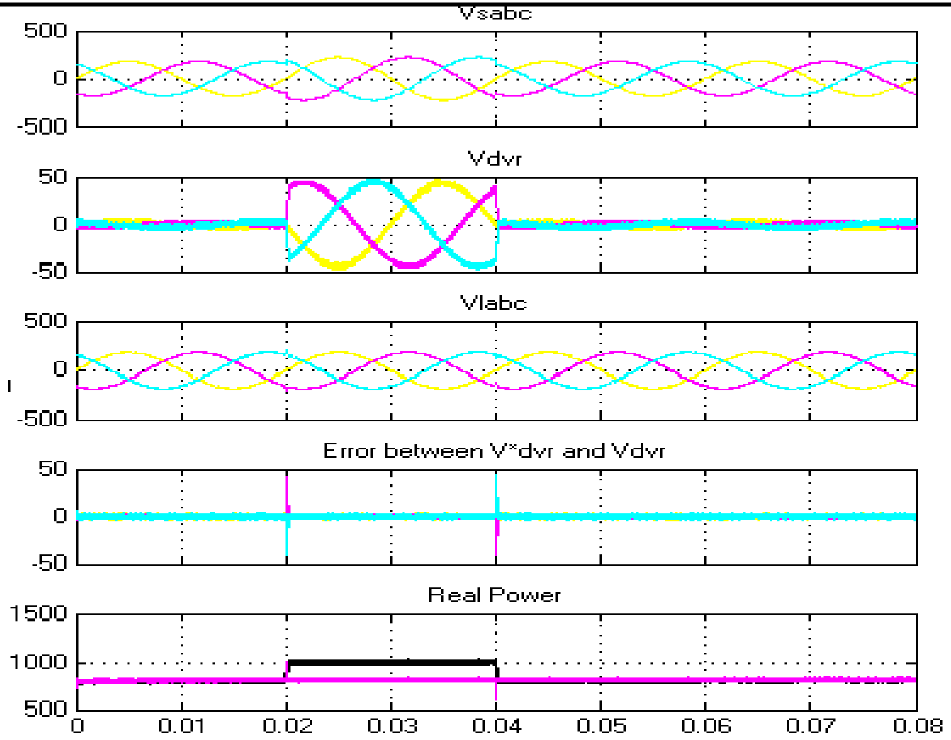

Fig.6 (a) Source voltages (V_{sabc}), 6(b) Injected voltages (V_{dvrinj}), 6(c) Load voltages (V_{labc}), 6(d) error between reference voltages and actual injected voltages and 6(e) real power

The modified Instantaneous DVR injected voltages (V_{dvrinj}) are shown fig.6 (b) and hence load voltages becomes pure sinusoidal without ripples shown in Fig.6 (c) with 0.27% total harmonic distortions. Finally by using adaptive hysteresis band voltage controller to Error between reference currents (V_{dvr}^{ref}) and Instantaneous injected currents (V_{inj}) are very less shown fig.6 (d).

V. CONCLUSIONS

This paper discuss the new concept of design and implementation of variable hysteresis band voltage controller for dynamic voltage controller by using simulation. The adaptive hysteresis voltage controller generates accurate injected voltages with help of system parameters and having low error value between reference injected voltages and actual injected voltages, smooth and no ripples in source currents. Hence by using adaptive hysteresis voltage controller for dynamic voltage controller to mitigate the all typical voltage problems. Hence adaptive hysteresis current controller is proved best method comparatively fixed adaptive hysteresis current controller.

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