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Dual Vector Control For Grid Interactive Converters In Smartgrid Under Unbalanced Conditions

Mrs. A.Sheela
Assistant Professor (SR.G)
Department of EEE & EIE
Kongu Engineering College

T.Saranyaa
PG Scholar
Department of EEE & EIE
Kongu Engineering College

Dr. S. Vijayachitra
Professor
Department of EEE & EIE
Kongu Engineering College

ABSTRACT—
The Voltage unbalance in a three-phase grid connected system causes performance deterioration of a pulse-width modulation (PWM) of Voltage source converter. It may also produce voltage ripples in the dc link and also increase the reactive power and have negative impact on grid current. In order to eliminate the voltage ripple along dc link capacitor and the dc component of the reactive power, both positive sequence and negative sequence currents should be controlled separately. Therefore this paper utilizes synchronous reference frame theory. One where the positive sequence currents are regulated by a proportional integral (PI) controller in a positive synchronous reference frame (SRF), and the other negative sequence currents are regulated by a PI controller in a negative synchronous reference frame. The positive reference frame which rotates counter clockwise, the positive sequence will appears as dc, while the negative sequence appears as 100 Hz. In same manner the negative sequence reference frame, which rotates clockwise, where the negative sequence appears as dc, while the positive sequence components appears as 100 Hz. So by eliminating 100-Hz AC components using an Anti-resonant filter in each SRF, one can measure positive sequence and negative sequence currents separately. The two controllers have been designed for controlling current separately. The demonstration and the effectiveness of the proposed control scheme are established by using simulation.

Keywords: — Current controller, dual control scheme, pulse-width modulation converter, symmetrical components, synchronous frame control scheme, voltage unbalance.

I. INTRODUCTION

In the past decade, DG based on renewable sources contributes for energy production. Now the integration of more renewable energy resources into the power grid requires more software to control and stabilize the grid under any voltages. The type of grid which is more intelligent is often termed as smart grid [8]. The main elements of the smart grid is energy storage which is required to stabilize the grids having a high percentage of variable, non-controllable energy sources such as wind or solar. The energy storage included in the network helps the network operator to stabilize and maintain grid. The different varieties for storing energy comprise ultra-capacitors, flywheels and batteries etc... This can be most often realised in the form of a voltage source converter (VSC) as shown in Fig 1.

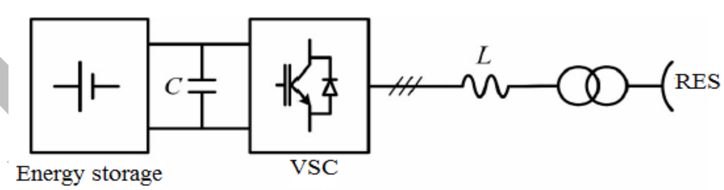

Fig 1: Energy storage connected with VSC

The voltage unbalance in a three-phase grid connected system will give rise to voltage ripples in the dc link and increases the reactive power and also affects the flow of active power to load. The existing method which used a feed-forward control algorithm for the pulse-width modulation (PWM) converter with

Unbalanced input supply and controlled in a positive reference frames [1]. In this paper two synchronous reference frames has been established which measure the positive sequence in the positive Synchronous reference frame by eliminating the negative sequence with a 100-Hz anti-resonant filter. In the same manner, the negative sequence has been controlled in the negative SRF. At the time of unbalance the currents are measured separately which uses two feedback proportional integral (PI) controllers. This separate control method technique implies the name as dual current controller. The current controller used which regulates only the positive sequence current in the positive SRF, and the other regulates only the negative-sequence current in the negative SRF. This method allows the negative-sequence current to be controlled completely in its own SRF as a dc signal and should track the 100-Hz ac command. The separate sequence components can be calculated by using accurate method.

II. MATHEMATICAL DESCRIPTION OF VOLTAGE SOURCE INVERTER UNDER UNBALANCED GRID VOLTAGES

When grid connected system is disturbed, due to voltage unbalance, phase jumps or any other amplitude variations occur, the system voltages and its currents could be represented by its positive and negative sequence components as shown. Therefore, an unbalanced system with three phase voltages (Va, Vb, Vc) could be represented with its positive ($v_{dq}^p = v_d^p + jv_q^p$) and negative sequence ($v_{dq}^n = v_d^n + jv_q^n$) components is given by

$$V_{\alpha\beta} = e^{j\omega t}.v_{dq}^p + e^{-j\omega t}.v_{dq}^n \qquad (1)$$

Where the grid voltage vector expressed in the stationary reference frame and ω is the angular grid frequency. In the same respective manner, unbalanced grid currents may also appear and they could be represented in terms of positive and negative sequence current components similar to (1) is given by

$$i_{\alpha\beta} = e^{j\omega t}.i_{dq}^p + e^{-j\omega t}.i_{dq}^n \qquad (2)$$

Where i_{dq}^p and i_{dq}^n is given as ($i_{dq}^p = i_d^p + ji_q^p$) and ($i_{dq}^n = i_d^n + ji_q^n$). The one case is represented for unbalanced voltage in the grid which is in its original and synchronously rotating reference frame is shown in Fig (2).

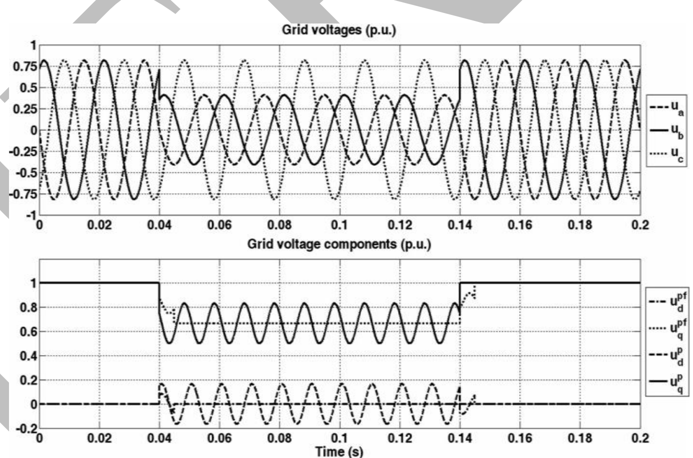

Fig 2: Phase voltages in original and synchronously rotating reference frame

The one main point to be in notice is that in the positive sequence reference frame positive component appears as dc, whereas a negative sequence component oscillates at twice the grid frequency. In negative reference frame, it is opposite to that of the positive reference frame. The representation of VSC at two levels which is used as an interface in energy storage applications which could be described by its differential equation (3) in the stationary reference frame,

$$u_{\alpha\beta} = v_{\alpha\beta} + L\frac{di_{\alpha\beta}}{dt} + Ri_{\alpha\beta} \qquad (3)$$

where R is grid resistance, L is grid inductance. The figure shown below represents the block of proposed method for control of VSC.

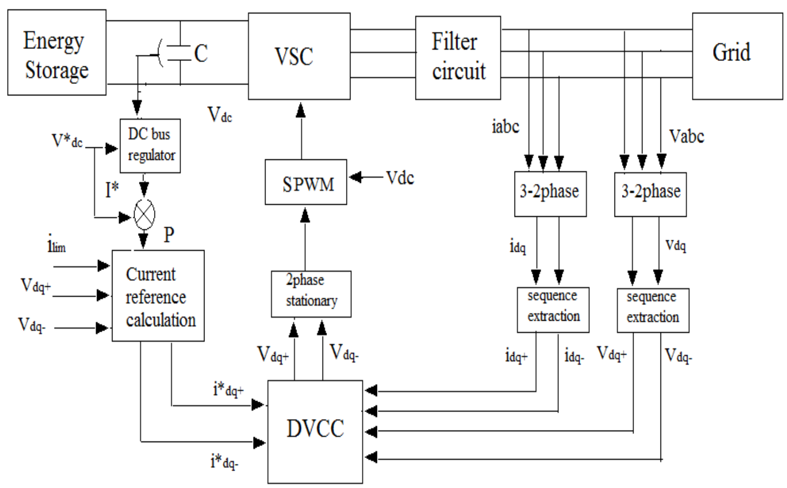

Fig 3: VSC control using DVCC Controller

Fig 3, illustrates the block for controlling of VSC under unbalanced conditions and to provide the active power flow to the load. $i_{\alpha\beta} = \sqrt{\frac{2}{3}}\,(i_a + i_b e^{\frac{j2\pi}{3}} + i_c e^{\frac{-j2\pi}{3}}$

$$v_{\alpha\beta} = \sqrt{\frac{2}{3}}\,(v_a + v_b e^{\frac{j2\pi}{3}} + v_c e^{\frac{-j2\pi}{3}} \qquad (4)$$

(5)

Where vαβ and iαβ denote the converter voltages and line currents respectively. Equation (3) can now be transformed and decomposed into two parts into positive and negative synchronous rotating reference frames respectively, as shown in the equations,

$$v_{dq}^{p} = L\frac{di_{dq}^{p}}{dt} + Ri_{dq}^{p} + j\omega L i_{dq}^{p} + v_{dq}^{p} \qquad (6)$$

$$v_{dq}^{n} = L\frac{di_{dq}^{n}}{dt} + Ri_{dq}^{n} - j\omega L i_{dq}^{n} + v_{dq}^{n} \qquad (7)$$

The instantaneous real and reactive power could be expressed using this as

$$S = v_{\alpha\beta}.\ i^{*}_{\alpha\beta} = P\ (t) + j.\ q(t) \qquad (8)$$

With the above active P (t) and reactive power Q (t), the equation obtained will be given as,

$$P(t) = P_o + P_{c2}.\cos(2\omega t) + P_{s2}.\sin(2\omega t) \qquad (9)$$

$$Q(t) = Q_o + Q_{c2}.\cos(2\omega t) + Q_{s2}.\sin(2\omega t) \qquad (10)$$

Where other coefficients are given by

$$P_o = 1.5(E_d^p I_d^p + E_q^p I_q^p + E_d^n I_d^n + E_q^n I_q^n) \qquad (11)$$

$$Q_o = 1.5(E_q^p I_d^p - E_d^p I_q^p + E_q^n I_d^n - E_d^n I_q^n) \qquad (12)$$

The high-order coefficients P_{c2}, P_{s2}, Q_{c2} and Q_{s2} which are the oscillation caused by the voltage unbalance are described above. Real power P is delivered to the DC link capacitor and it determines the level of voltage. Consequently, P (t) varies with time for P_{c2} and P_{s2} not being equal to zero and therefore its dc link voltage fluctuates [3]. Expressing the power coefficients in the matrix form, the obtained matrix will be,

$$\begin{bmatrix} \frac{2}{3}P_o \\ \frac{2}{3}Q_o \\ \frac{2}{3}P_{s2} \\ \frac{2}{3}P_{c2} \end{bmatrix} = \begin{bmatrix} E_d^p & E_q^p & E_d^n & E_q^n \\ E_q^p & -E_d^p & E_q^n & -E_d^n \\ E_q^n & -E_d^n & -E_q^p & E_d^p \\ E_d^n & E_q^n & E_d^p & E_q^p \end{bmatrix} \begin{bmatrix} I_d^p(t) \\ I_q^p(t) \\ I_d^n(t) \\ I_q^n(t) \end{bmatrix} \qquad (13)$$

By removing voltage ripple across dc link and achieving the average zero reactive power. The control objectives that can be fulfilled by choosing currents such that

$$\begin{bmatrix} I_d^p(t) \\ I_q^p(t) \\ I_d^n(t) \\ I_q^n(t) \end{bmatrix} = \begin{bmatrix} E_d^p & E_q^p & E_d^n & E_q^n \\ E_q^p & -E_d^p & E_q^n & -E_d^n \\ E_q^n & -E_d^n & -E_q^p & E_d^p \\ E_d^n & E_q^n & E_d^p & E_q^p \end{bmatrix}^{-1} \begin{bmatrix} \frac{2}{3}P_o \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (14)$$

$$= \frac{2P_o}{3D} \begin{bmatrix} E_d^p \\ E_q^p \\ -E_d^n \\ -E_q^n \end{bmatrix} \qquad (15)$$

Where $D = \left[(E_d^p)^2 + (E_q^p)^2\right] - \left[(E_d^n)^2 + (E_q^n)^2\right]$

With a current choice of (14), the higher order coefficients will vanish. This can be provided as the input current reference to the controller.

III. DUAL VECTOR CURRENT CONTROL BASED ON POSITIVE AND NEGATIVE SRF'S

The proposed control method requires rapid and precise separation of positive and negative sequences. For this reason signal delay cancellation method is used [13]. The three phase abc system is first transformed into its Stationary αβ reference frame using Clark transformation and then it is delayed for T/4 [5]. The fig 4 describes the block diagram of signal delay cancellation method for sequence separation.

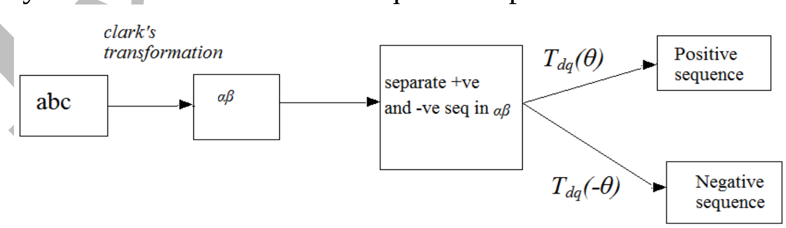

Fig 4: Block for signal delay cancellation method

The positive and negative sequences components can be calculated by using above method. From the above equation, T- is the period of the fundamental frequency.

$$\begin{bmatrix} v_\alpha^+(t) \\ v_\beta^+(t) \\ v_\alpha^-(t) \\ v_\beta^-(t) \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \end{bmatrix} * \begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \\ v_\alpha(t-\frac{T}{4}) \\ v_\alpha(t-\frac{T}{4}) \end{bmatrix} \qquad (16)$$

The positive and negative sequences in equation (16) is of stationary αβ reference frame can be further transformed into positive dq and negative dq sequences using

$$\begin{bmatrix} v_d^+ \\ v_q^+ \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} * \begin{bmatrix} v_\alpha^+ \\ v_\beta^+ \end{bmatrix} \qquad (17)$$

$$\begin{bmatrix} v_d^- \\ v_q^- \end{bmatrix} = \begin{bmatrix} \cos(-\theta) & \sin(-\theta) \\ -\sin(-\theta) & \cos(-\theta) \end{bmatrix} * \begin{bmatrix} v_\alpha^- \\ v_\beta^- \end{bmatrix} \qquad (18)$$

From the above equation the positive and negative sequence is obtained. The Simulink model of signal delay cancellation method obtained in MATLAB is given below

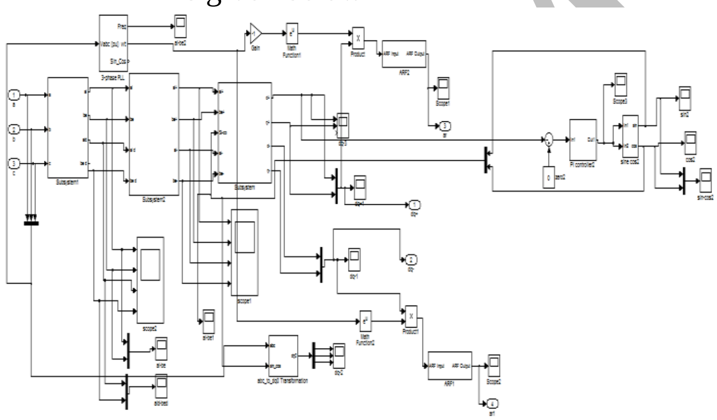

Fig 5: Simulink model of signal delay cancellation method.

The $v_d^+, v_q^+, v_d^-, v_q^-$ represents both positive dq and negative dq sequence components.

From this equation, dc component has to be filtered out by using filter. The output waveform of Vdq+ and Vdq- is obtained as

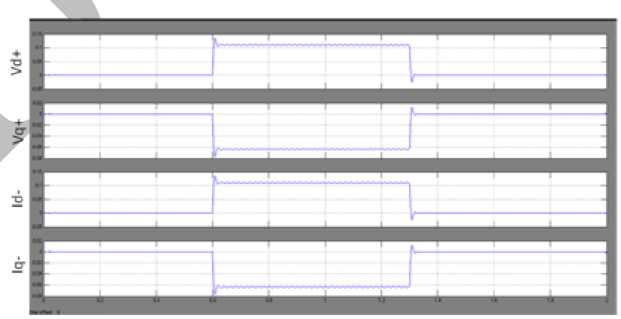

Fig 6: Output of Vdq+ and Vdq-

A) ANTI RESONANT FILTER

Positive and negative voltage and current components can be extracted from the measured grid voltages $v_{\alpha\beta}$ and currents $i_{\alpha\beta}$ after employing transformation of rotation to positive ($e^{-j\omega t}$) and negative ($e^{j\omega t}$) reference frame respectively. The sequence voltages are given by

$$v_{\alpha\beta}.e^{-j\omega t} = v_{dq}^{p} + v_{dq}^{n}.e^{-j2\omega t} \qquad (19)$$

$$v_{\alpha\beta}.e^{j\omega t} = v_{dq}^{p}.e^{j2\omega t} + v_{dq}^{n} \qquad (20)$$

It can be seen that in positive reference frame, apart from positive components v_{dq}^{p} that appear as DC values, and there are also negative sequence components v_{dq}^{n} at twice the grid frequency. In the negative reference frame it is vice versa. AC components in the above sequence equation have to be removed. One of the possible solutions is the application of anti-resonant filter (ARF) [14] and its control diagram is shown in Fig 7.

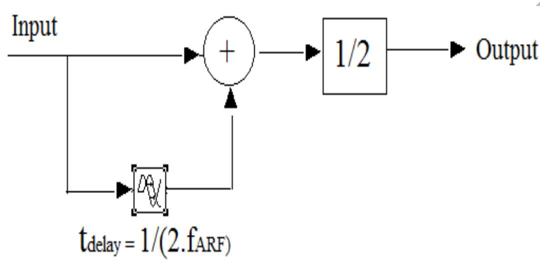

Fig 7: Block of Anti-resonant filter

B) DUAL VECTOR CONTROLLER

The controller used here is dual vector current controller for controlling the positive sequence and negative sequence components separately and simultaneously. The positive sequence components are controlled in the positive SRF, while the negative sequence components were controlled in the negative SRF. The current commands will appear as dc in their reference frame and there was no need to build a tracking controller for an ac signal. The DVCC controller is nothing but a pair of PI controllers that control the positive and negative sequence components separately in their positive and negative sequence controller. The input to the controller is the filtered out components from AR filter [4]. The current reference calculation and filtered dc current component is compared and error generated is given to the PI controller for both positive and negative sequence controller separately. Fig 8, illustrates the representation of design of Dual vector current controller.

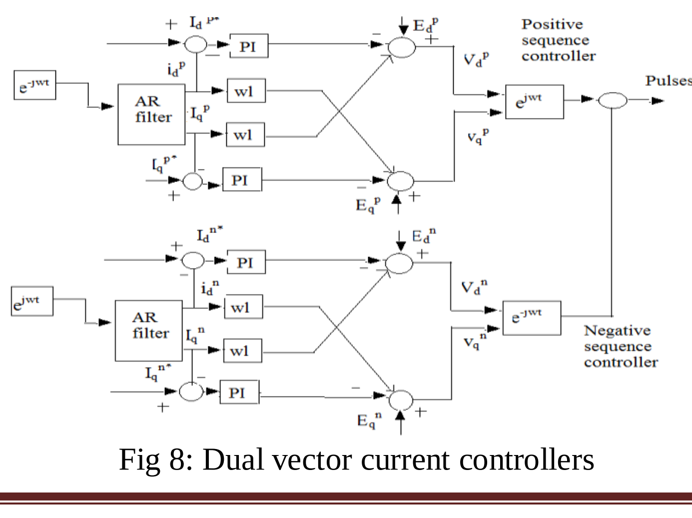

Fig 8: Dual vector current controllers

The output from the positive sequence controller is given by

$$v_d^p = E_d^p - (PI)\left(I_d^{p*} - I_d^p\right) + \omega L I_q^p \qquad (21)$$
$$v_q^p = E_q^p - (PI)\left(I_q^{p*} - I_q^p\right) - \omega L I_d^p \qquad (22)$$

The output from the negative sequence controller is given by

$$v_d^n = E_d^n - (PI)(I_d^{n*} - I_d^n) - \omega L I_q^n \qquad (23)$$
$$v_q^n = E_q^n - (PI)\left(I_q^{n*} - I_q^n\right) + \omega L I_d^n \qquad (24)$$

The output equation (21), (22) and (23), (24) from the dual vector controller is multiplied with $e^{j\omega t}$ and $e^{-j\omega t}$ to obtain the stationary reference frame voltage. The terms $\omega L I_q^p, -\omega L I_d^p, -\omega L I_q^n, \ \omega L I_d^n$ are inserted to decouple the axes dynamically. The procedure of obtaining voltage components $(E_d^p, E_q^p, E_d^n, E_q^n)$ is identical to that of obtaining the current components.

IV. SPACE VECTOR MODULATION

The Space-vector pulse-width modulation (SVPWM) strategy is a mainstream for three-phase voltage source inverters (VSIs). The Space-vector pulse-width modulation technique can be simplified by adding a voltage offset to the phase voltages. The output from the dual vector controller is multiplied with $e^{j\omega t}$ and $e^{-j\omega t}$ to obtain the stationary reference frame voltage.

$$V_{sp} = \left(v_d^p + jv_q^p\right)e^{j\omega t} + (v_d^n + jv_q^n)e^{-j\omega t} \qquad (25)$$

According to the voltage generated from the controller the pulse is given to the converter for operation under unbalanced condition.

V. SIMULATION RESULTS

The Simulation output and result for unbalanced condition with controller is shown,

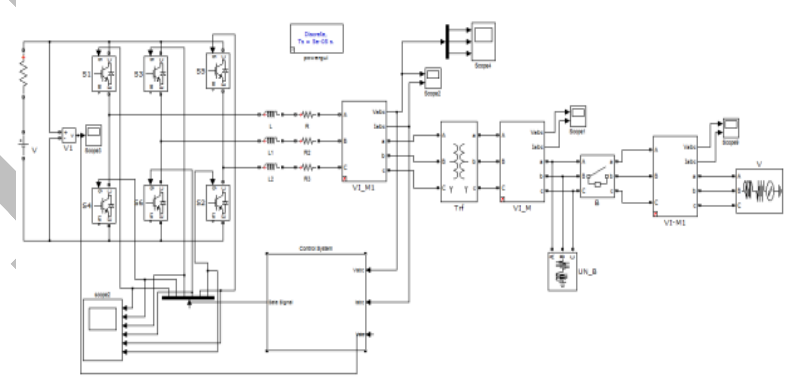

Fig 9: The simulation diagram with controller to mitigate unbalance condition

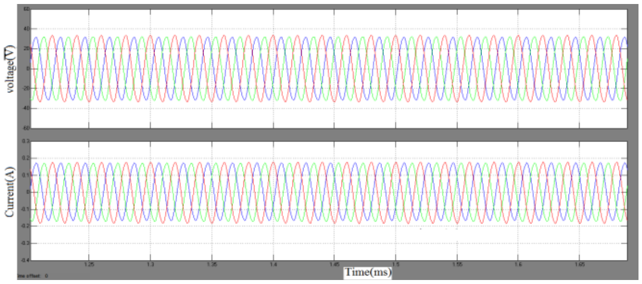

Fig 10: The MATLAB output with controller

The characteristic of unbalanced fault is the appearance of negative sequence component in the grid voltages and this give rise to double frequency oscillations in the power system which are reflected as ripple in the dc-link voltage and output power

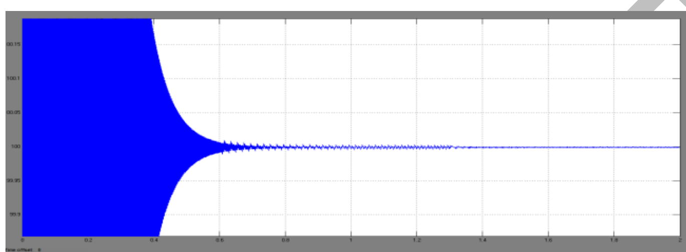

Fig 11: Output of dc link capacitor voltage under unbalance

The DVCC controller performs the mitigation of unbalance voltage conditions when it is connected to grid and it also suppresses the oscillations and ripples in DC link capacitor, the output of which is shown in figure 12.

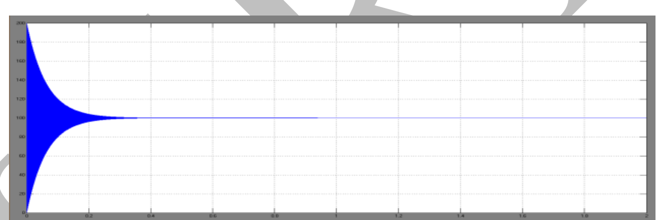

Fig 12: Output of dc link capacitor voltage under unbalance with controller

VI. REFERENCES

This paper proposed power flow control strategies for energy storage connected to smart grid under unbalanced conditions. The voltage unbalance in the three-phase grid connected power system give rise to voltage ripples in the dc link capacitor and oscillation at twice the grid frequency which had been eliminated by design of DVCC controller. The DVCC controller has been designed and the unbalance is mitigated. By fast and accurate method of sequence separation, the negative sequence impact is avoided by the design of controller. The controller work efficiently and it is accurate to operate under unbalanced conditions. The simulation results had been provided. The DVCC controller plays a major role in power system under unbalanced condition.

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