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Vector-Controlled Back-To-Back VSC System in the Grid Disturbance of HVDC Transmission Line

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ABSTRACT

A voltage-source converter (VSC) is the main building block for flexible ac transmission systems (FACTS) devices and, as of today HVDC technology up to hundred megawatts. This paper specifically proposes a control structure to improve the performance of high-power vector-controlled back-to-back VSC systems for driver applications, wind generators and for transmission systems applications The main improvement is to suppress the possible dc-link voltage fluctuations under power line faults and unbalanced conditions. The proposed controller structure is designed based on regulating the converter system's states locally in d-q synchronous reference frame without sequence components extraction

Index Terms -High-voltage direct current (HVDC), Back-To-Back (BTB), Voltage Source Converter (((VSC)

I. INTRODUCTION

It is desirable to have high-power high-voltage converter based systems available during power system faults when they may be needed the most. Voltage-source converter (VSC)-based transmission systems have attractive potential features in terms of power flow control and stability of the network. A voltage-source converter (VSC) is the main building block for flexible ac transmission systems (FACTS) devices and, as of today HVDC technology up to several hundred megawatts. Although relatively low switching frequency operation of high-power converters is desirable, it makes them sensitive to power network imbalances when they may be needed the most

This paper specifically proposes a control structure to improve the performance of high-power vector-controlled back-to-back VSC systems for conventional and emerging utility applications. The main improvement is to suppress the possible dc-link voltage fluctuations under power line faults and unbalanced conditions. The increasing emergence of VSC-based transmission is the result of development in semiconductor devices, power electronic circuits, control, and executive engineering. Previously, the lack of these developments had prohibited the VSC-based technology from being the first choice. While each development is moving forward individually, the result of each one influences the design criteria and application requirements of the overall system. To the best of the authors' knowledge, in the installed operating FACTS and HVDC systems, the ride-through capability is obtained either by proper passive element design or a change in the control mode. On the other hand, with emerging high-power applications such as 10-MW wind generation turbines or transportable recovery transformers, the dynamic operation of the VSC under power system disturbances must be revisited.

This paper proposes an alternative control framework to obtain robust dc-link voltage with specific attention to design the VSC controller in the back-to-back (BTB) configuration. The proposed controller is implemented in

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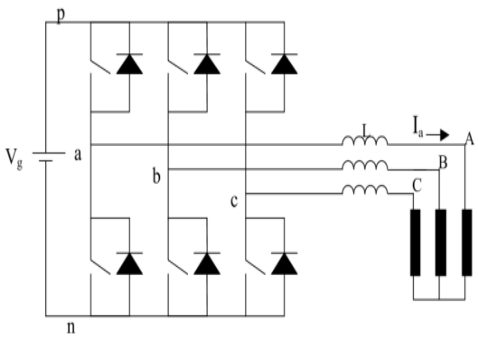
the *d-q* (rotating) synchronous reference frame without sequence extraction System. The proposed controller structure is designed based on regulating the converter system's states locally in *d-q* synchronous reference frame without sequence components extraction or resonant notch compensator

III. MODELING OF VSC



The modeling of VSC, the building block of the BTB system, is based on the state-space average modeling approach. This modeling is based on the principal circuit analysis and voltage and current equations for storage elements known as state equations. the state equations of a VSC in the three- phase stationary coordinates are as follows:

$$\frac{dIabc}{dt} = -\frac{Rs}{Ls}Iabc + \frac{Eabc}{Ls} - \frac{Vabc}{Ls} \ldots\ldots\ldots(1)$$

$$\frac{dVDc}{dt} = \frac{IDc}{CDc} - \frac{VDc}{RpCDc} - \frac{P_{Load}}{VDCCDc} \ldots\ldots\ldots\ldots\ldots(2)$$

In order to benefit from all decoupling and constant properties of a two-phase system instead of a three- phase one, d-q transformation is considered to convert all quantities in the abc stationary coordinate frame to the synchronously rotating reference frame, i.e., de–qe

$$\frac{dId}{dt} = -\frac{Rs}{Ls}Id - ws\,Iq + \frac{Ed}{Ls} - \frac{Vd}{Ls} \ldots\ldots\ldots(3)$$

$$\frac{dIq}{dt} = -\frac{Rs}{Ls}Iq + ws\,Id + \frac{Eq}{Ls} - \frac{Vq}{Ls} \ldots\ldots\ldots\ldots(4)$$

In (3) and (4), *Vd* and *Vq* are the converter output voltages in the synchronous reference frame. The modulation index can also be written in this frame as

(5) where *k* depends on the modulation technique. In this study, we use the vector control method or type-I control

$$md = \frac{Vd}{kVDc}, mq = \frac{Vq}{kVDc} \ldots\ldots\ldots\ldots\ldots(5)$$

In many literature works especially for dc/dc converters, the modulation index is used as the control input; therefore, (3) and (4) present the nonlinear system. DC-link dynamics are also nonlinear by introducing the definition for *I*DC as (6). However, by considering Vd and Vq as the control inputs, (3) and

(4) can be treated as linear ones. Also, power balance is used to derive the equation for the dc-link voltage neglecting the interface losses as in (7). *Ea* (the PCC phase A voltage) is aligned with the *d*-axis in the

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synchronously rotating reference frame.

The result of dc-link dynamics shown in (7) is linear as long as *Ed* and *Eq* are constant. Consequently, no linearization around specific operating points is needed and the small-signal VSC

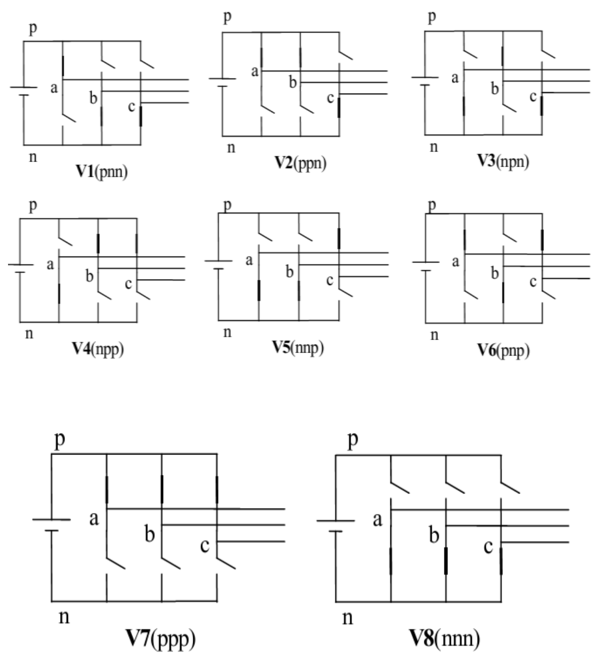

Fig.2.2.Eight switching topology of voltage source Inverter.

Model looks similar to the large-signal model. The state-space representation of the VSC can be obtained from (3), (4), and(7). State variable vector *x*(*t*) is the state variable vector, *u*(*t*) is the input vector, and *e*(*t*) is considered as the disturbance vector, (8)

$$\boldsymbol{I}Dc = \frac{3}{2}(mdId + mqIq) \quad \dots\dots\dots\dots\dots\dots (6)$$

$$\frac{dV^2Dc}{dt} = \frac{3EdId}{CDc} + \frac{3EqIq}{CDc} - \frac{2V^2Dc}{RpCDc} - \frac{2Pload}{CDc} \dots\dots\dots\dots (7)$$

$$X(t)=\begin{pmatrix} Id \\ Iq \\ V^2Dc \end{pmatrix},\ u(t)=\begin{pmatrix} Vd \\ Vq \end{pmatrix},\ e(t)=\begin{pmatrix} Ed \\ Eq \\ Pload \end{pmatrix} \dots\dots\dots\dots (8)$$

In the vector-controlled BTB VSC systems regardless of the topology, one converter typically controls the dc-link voltage and supports its reactive power. This converter can be operated as rectifier in HVDC applications or as an inverter in direct driven wind turbines. The other converter is operated in *PQ* or *V/f* (voltage/frequency) mode controlling the active and reactive powers. A simplified schematic of the BTB VSC system with its control. To design a closed-loop system, the Eigen structure assignment or any linear feedback design method can be used to place the poles at the desired locations. Eigen structure assignment is explained for STATCOM and we use it to develop the general controller and as the baseline for the VSC in the BTB configuration as presented. According to the system equations, the mode associated with the *q*- component of the current (typically for reactive power control) can be adjusted based on the ac-side interface parameters and required response time.

On the other hand, dc-link voltage closed- loop dynamics consist of the modes associated with two Eigen

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values. One of the system poles affects the charging and discharging of the capacitor which is called λc . This Eigen value should be placed near to the origin to avoid either high charging or discharging current. The other pole can be placed at the same location the reactive current control mode is, which we call it λi . It should be noted that the poles associated with the current mode can be placed as far as the inherent delay of the converter modeling allows; current regulators often present a fast first order behavior. To achieve a non oscillatory output response, it is sufficient to place the poles at the real axis. Consequently, the dc-link voltage regulator can be designed based on the system specifications and requirements. The performance of the BTB system under balanced conditions through the proposed modeling and control.

TABLE .I. VSC BTB SYSTEM PARAMETERS

Base power	S	10 MVA
Line-to-line voltage(converter side)	E	1pu=13.8 kv
Line-to-line voltage for drive application	E_w	1pu=3.3 kv
Line frequency(grid)	F	60Hz
Leakage inductance	L_s	15%pu
Interface resistance	R_s	0.4%pu
DC link voltage	V_{DC}	1pu=1.65V_{AC}
DC link capacitance	C_{DC}	0.66pu
Unit capacitance constant	H	4.14ms
Switching frequency	f_s	900Hz(15xf)
Converter loss resistor(estimated)	R_p	1%pu
Continuous over current capability	I	1.5pu
Absolute over current capability	I_{max}	2pu
Current controller pole location	Λi	-1000
Voltage controller pole location	Λc	-250
Communication delay	T_d	10ms
Time delay of the derivatives	T_{iF}	0.1ms
Controller sampling time	t_s	50us

IV. SPACE VECTOR MODULATION

The desired three phase voltages at the output of the inverter could be represented by an equivalent vector V rotating in the counter clock wise direction as shown in Fig.3.1 (a). The magnitude of this vector is related to the magnitude of the output voltage (Fig. 3.2(b)) and the time this vector takes to complete one revolution is the same as the fundamental time period of the output voltage.

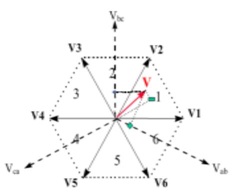

Fig 3.1(a)

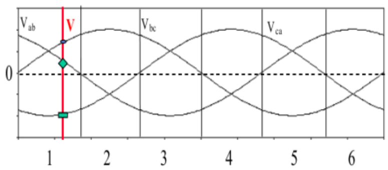

Fig3.2(b)

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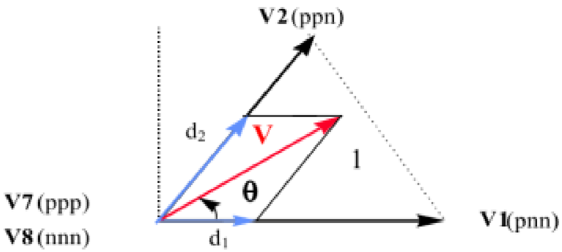
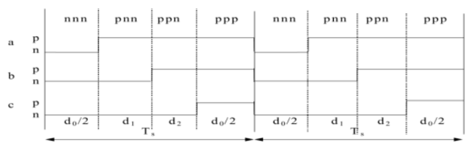
Let us consider the situation when the desired line-to-line output voltage vector V is in sector 1 as shown in Fig. This vector could be synthesized by the pulse-width-modulation (PWM) of the two adjacent SSV's V1(pnn) and V2 (ppn), the duty cycle of each being d1 and d2, respectively, and the zero vector (V7(nnn) / V8(ppp)) of duty cycle d0:

$d_1 V_1 + d_2\ V2 = V = m\ V_g\ e^{je}$

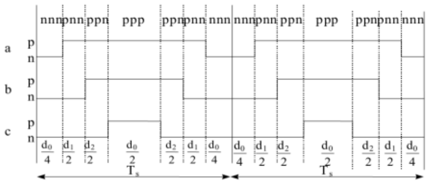
$d_1 + d_2 + d_0 = 1$

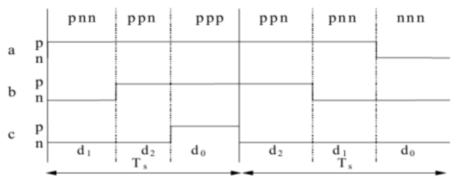
Where, 0.866 ≤ m ≤ 1 , is the modulation index. This would correspond to a maximum line-to-line voltage of 1.0Vg, which is 15% more than conventional sinusoidal PWM as shown.



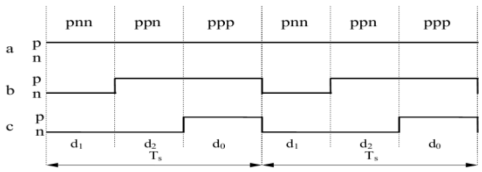


SVM1.


SVM2.



SVM3.



SVM4

V.CLOSED-LOOP BACK-TO-BACK VSC SYSTEM

5.1. Introduction

It Is desirable to have high-power high-voltage converter based systems available during power system faults when they may be needed the most. If the protection measures trip the converter system, it can take several fractions of an hour, depending on the size of the converter, to discharge the dc link and check the healthiness of the whole system. Hence, several practical methods have been proposed and implemented to keep a system operating under power system faults and disturbances .Today, the most promising market for HVDC technology is interconnection of the networks where the centers of the loads are located far from the points of connection. The problem of ac systems arises as the phase angle drifts and varies over a wide range with daily load changes. This phenomenon especially in a weak ac network along with the power line faults exacerbates the operation of HVDC systems. A voltage-source converter (VSC) is the main building block for flexible ac transmission systems (FACTS) devices and, as of today HVDC technology up to several hundred megawatts.

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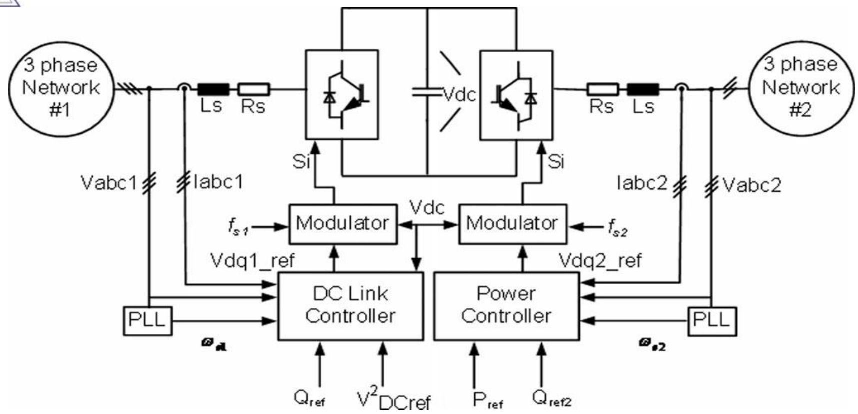

Fig.5.1 . Simplified schematic of closed-loop BTB VSC systems.

The increasing emergence of VSC-based transmission is the result of development in semiconductor devices, power electronic circuits, control, and executive engineering. Previously, the lack of these developments had prohibited the VSC-based technology from being the first choice. While each development is moving forward individually, the result of each one influences the design criteria and application requirements of the overall system. However, generally, less dependence on power semiconductor characteristics amounts to having more supplier possibilities for the VSC-based transmission.

The most important limiting factor of power semiconductors is their switching properties since they are usually optimized for the conduction intervals. Hence, high-power electronic converters are desired to operate with relatively low switching frequencies (maximum 9–15 times the line frequency, and even lower for multilevel converters).

The low switching frequency operation of VSC systems imposes control limitations in case of power system faults and disturbances when they may be needed the most. To the best of the authors' knowledge, in the installed operating FACTS and HVDC systems, the ride-through capability is obtained either by proper passive element design or a change in the control mode. On the other hand, with emerging high-power applications such as 10-MW wind generation turbines or transportable recovery transformers, the dynamic operation of the VSC under power system disturbances must be revisited.

This project proposes an alternative control framework to obtain robust dc-link voltage with specific attention to design the VSC controller in the back-to-back (BTB) configuration, as shown in Fig. 5.1. The proposed controller is implemented in the d-q (rotating) synchronous reference frame without sequence extraction. The rest of this project is organized as follows. It reviews research and advances to control the VSC under unbalanced conditions. This section also provides the backgrounds and advantages of the proposed methods and their applicability for high-power high-voltage VSCs. Describes the modeling approach for the VSC. In this , general closed loop functions and control constraints of the BTB VSC systems will be discussed briefly. the proposed control architecture and its implementation will be presented. RTDS verification of the proposed control method on the BTB VSC system for different applications will be presented , Finally presents the conclusion of this paper.

5.2 Backgrounds On Controlling The Vsc Under Unbalanced Conditions

A. Single VSC Control Under Unbalanced Conditions

The VSC is the main building block for FACTS devices and many other converter-based utility interfaces. Therefore, the study on the methods to improve the converter performance as a single system under network unbalanced conditions is unavoidable. The theory of instantaneous active and reactive powers for three-phase switching converter control was proposed by Akagi et al. It has been shown that the power quality in terms of current harmonics and reactive power can be improved using the instantaneous reactive power definition. The work showed that network voltage unbalances cause input current distortions which can be transferred to the dc side due to the negative-sequence component of the voltage.

An example of negative-sequence appearance in the positive-sequence d-q synchronous frame is shown in Fig. 4.2. Rioual et al. Probably proposed the very first control scheme for the VSC that regulates the instantaneous power generated under network voltage dips. Their work mainly generated current references in both positive and negative synchronous references to regulate the power at the point of common coupling (PCC). Since then, researchers have been developing "enhanced" control schemes mostly to minimize input harmonics which are coupled to dc-link voltage ripples. For instance, Stankovic and Lipo presented a model that can eliminate the harmonics for generalized unbalanced conditions.

However, this method needs a great deal of computation steps for DSP-based control. The authors consider the instantaneous power at the converter poles, not the PCC, and consequently obtain better harmonic responses. Although these methods are more effective than the work and relatively simpler. The proposed methods suffer from solving nonlinear equations in real time and low bandwidth of the current regulator due to the extraction of the current sequence components. Suh and Lipo continued their work, which resulted in a hybrid synchronous stationary frame with oscillating reference currents. Consequently, the bandwidth-diminishing functions are avoided.

They also proposed a simplified current reference generator that can be implemented more easily than that. It might be of reader's interest that , the instantaneous reactive power definition is different from the "classical" notion of outer products of vectors presented . Instead, these authors mainly employed the work in which the authors developed the so-called extension PQ theory to resolve the singularity issues existing in the work of Akagi et al. for the generalized unbalanced condition. Accordingly, the instantaneous reactive power is redefined on the basis of a set of voltages that lag the pole voltages by 90◦ and is not the imaginary part of the complex power. Despite satisfactory operation of a three-phase rectifier under unbalanced conditions, the proposed scheme requires several feedback and feed forward compensators.

A simplified controller is proposed in which uses stationary current controller (resonant compensator) that considers both positive and negative sequences simultaneously. Notch filters tuned at 120◦ are nonetheless used to extract the bus voltage sequences for current reference generation. The authors also consider notch filters but to separate the positive- and negative-sequence current controllers. One potential constraint of these methods is the emergence of third harmonic in the input current that is proportional with the voltage dip, an the authors analyzed the effects of several methods to estimate the proper sequence components.

Most recent work is reported which implemented the whole control frame in the stationary frame resulting in a new current reference generator. Fast dynamic performance with small dc-link voltage ripple in a 20-kVA/10-kHz pulse width modulation (PWM) prototype converter under a 30% supply voltage dip is reported. A desirable feature of the scheme is that no phase-locked loop (PLL) strategies are needed but constant line frequency is assumed and sinusoidal compensators as are deployed due to the control logic of the oscillating references.

B. BTB VSC Control Under Unbalanced Conditions

The transmission-level multi-VSC option requires a careful consideration of system interactions, while switching frequency is kept relatively low (9–15 times the line frequency). An example of this theme is investigated for a unified power flow controller (UPFC) where additional compensating terms are added to reduce or remove the interactions of rectifier and inverter. The interaction has been highlighted as one of the potential issues of BTB VSC system operation with conventional controllers applied to single VSCs. This fact is more critical under power system faults since the controllers introduced previously should take these interactions into account.

Therefore, simply separating sequence controllers may not achieve the desired performance due to the system coupling, filtering delays, etc. To solve these problems, introduced a framework which mainly used the results. Xu et al proposed to nullify the oscillating power by generating a current reference. In addition, Xu et al. considered the improved "cross-coupling control" mentioned for UPFC . This control scheme was first proposed for UPFC applications where authors showed that the crossing gain of a transmission line is much larger than its direct gain. The cross-coupling controller uses the *q*-axis voltage vector, to control the *d*-axis current and the *d*-axis voltage vector to control the *q*-axis current. Numerical results illustrate the satisfactory performance under a single-line-to-ground fault but with more than double the rated current.

The latter result is important in VSC HVDC transient dynamics. It has been pointed out in that increase of the current limit significantly improves the power quality of the system. Yazdani and Iravani mention that it is possible to suppress the dc-link voltage oscillations by using the notch filter approach; therefore, the same issues exist as for a single VSC. For a specific VSC BTB HVDC system, Hagiwara and Akagi proposed a unique dc link control structure that has the load feed forward term. With the proposed structure, a robust dc-link voltage is achieved if the fault occurs in the inverter side. It has been shown that load estimation can improve the converter performance. In fact, Winkelnkemper had shown that adding the load estimation into the main controller better attunes the dc-link voltage to load power change. Parkhideh et al. Also showed how it is possible to remove the varying load effect from the closed-loop large mining converter control systems (1.5–24 MW) which are basically BTB VSC systems.

On the other hand, there are emerging interests to have medium voltage interfaces for renewable integration such as wind generations currently up to 10MVAwith direct-drive technologies (BTB VSC). The authors have presented a unique controller in the stationary frame for direct-drive wind generation systems that is based on reactive power compensation.

Applying the proposed method ensures balanced grid currents even under power system faults. Nonetheless, due to possible low-speed operation of wind turbines, dc-link dynamics have been addressed as one of the key factors which affect the operation of the turbine. Therefore, more investigations are essential to determine the proper control strategy:

Balanced currents or a stiff dc-link voltage. This project proposes a control structure specifically for the dc-link controller converter in the BTB VSC system which is implemented in a single synchronous reference frame without any sequence component extraction or resonant compensator. It will be shown that dc-link dynamics are

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coupled to the interaction imposed by the inverter performance. On the other hand, there is no direct control input that can remove this interaction or disturbance with conventional frequency-oriented controller design. This study introduces a d-q (rotating) synchronous-based framework to design a more robust controller for relatively low switching frequency (9–15 times) PWM or vector-controlled BTB VSC systems.

5.3 Modified Bsc For Btb Vsc Systems

In this section, the proposed controller based on the local control of the converter states will be explained, first for reactive power control to clarify the method.

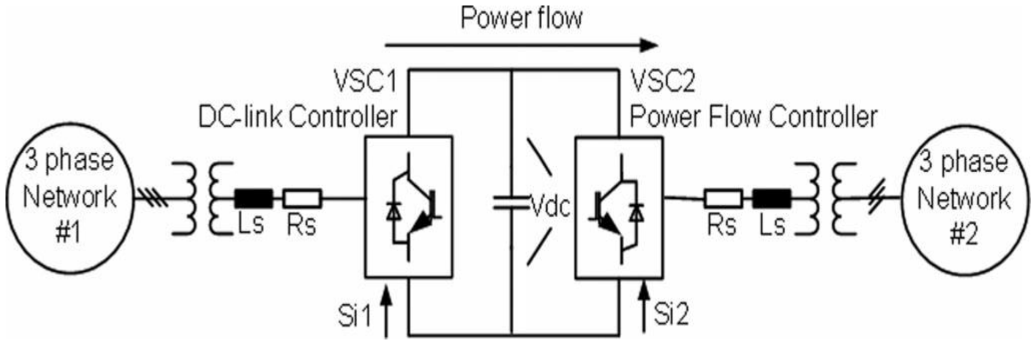


Fig. 5.2. BTB VSC System For HVDC Applications.

The reactive power controlled by the *q*-component of the current has a direct input Vq as shown in (5.2). This controller is desired to have decoupled and disturbance rejection characteristics while achieving the required response time. This criterion is met if its input Vq has the form of (5.1).

The first term in this equation is responsible for the response time of the state and the remaining terms are for decoupling, disturbance rejection, and command following in order. The result of first-order system is shown in (5.2), which is also available in the literature. The direct input for the *d*-component of the current, Vd , is first designed to have decoupling and disturbance rejection terms as in (5.3). The additional term Ψ1 is used as the control input to regulate the dc-link voltage and active power through a back stepping control method.

$$V_d=-f_q I_q+L_s w_s I_d+E_q+t q I_{qr} \quad \text{-----} \quad (5.1)$$

$$¡q=\left(\frac{R_s+f_q}{L_s}\right) I_q-\frac{tq}{L_s} I_{qref} \quad \text{------}(5.2)$$

$$V_d=-L_s w I_q+E_d+\Psi 1 \quad \text{--------}(5.3)$$

$$¡d=-\frac{Rs}{Ls} I_d-\frac{1}{Ls}\Psi 1 \quad \text{--------}(5.4)$$

In control theory, back stepping is a technique for designing controls for nonlinear systems developed around 1990. It is a recursive technique in which one designs feedback controls and finds Lyapunov functions for a set of *n* increasingly complex systems, the last system being the one of interest. An example of using this method on a three-phase PWM rectifier can be found in.

The fundamental idea can be interpreted as the local control of the states that do not access to the input. In other words, some states are used as a pseudo control to stabilize others by introducing some virtual state variables representing the difference between the actual and virtual control. Accordingly, *β* defined below is used to control dc-link voltage which does not have direct control input, as shown in (5.5) and (5.6). The change of the coordinates here to *z* indicates that *β* should take whatever value is required to make the error *z*1 null corresponding to achieving the reference *z*3 (stable dc-link

Voltage)

$$z3 = V^2Dc \qquad \text{-----(5.5)}$$

$$z1 = \beta - \alpha(z3, Eq, Pload) \qquad \text{---(5.6)}$$

where

$$\beta = \frac{3EdId}{CDc} \text{--} \qquad \text{---(5.7)}$$

This method is valid only at the level of the Lyapunov function. The selected candidate functions are based on the energy concept of the dc-link capacitor and the interface inductor. If the defined state for the dc-link voltage is considered to be *V* 2 DC, it is sufficient to propose the candidate functions as (5.7) and (5.8) which are positive-definite functions.

$$V_3 = \frac{1}{2} z^2 3 \ \text{-} \qquad \text{---(5.8)}$$

$$V_1 1 = V_3 + +\frac{1}{2} z^2 1 \qquad \text{..........(5.9)}$$

It is remarkable that it is not the key of choosing the virtual and actual controls but choosing the correct Lyapunov functions and generating their derivatives negative to ensure the stability of the whole system. The virtual control input is chosen as (5.9) to meet these requirements

$$\alpha(z3, Eq, Pload) = -\mathbf{f}vDCz3 - \frac{3EqIq}{CDc} + \frac{2Pload}{CDc} + \mathbf{f}vDCV^2Dc\,ref \qquad \text{-----(5.10)}$$

The derivative of the proposed Lyapunov functions combining (5.1) and (5.5)–(5.9) results in

$$\dot{V}3 = z3\dot{z}3 = z3(z1 + \alpha + \frac{3\dot{E}qIq}{CDc} - \frac{2V^2Dc}{RpCDc} - \frac{2Pload}{CDc}) \qquad \text{------(5.11)}$$

$$\dot{V}1 = \dot{V}3 + z1\dot{z}1 = V3 + z1(\beta\left(\frac{Ed}{Ed} + -\frac{\dot{R}s}{Ls}\right) + -\frac{3Ed}{LsCDc}\Psi 1 - \alpha) \ \ldots\ldots (5.12)$$

Choosing the input signal Ψ1 *(t)* as (5.11), in which we define the controller gain as fd and replaced β from (5.6), leads to having $\dot{V}1$ and $\dot{V}3$ in the form of (5.11) and (5.12) which ensures the stability of the virtual controllers *z*1 and consequently the system. In other words, the derivative functions become negative definite, assuring the stability of the system.

$$\Psi 1 = -\frac{LsCDc}{3Ed}(-\mathrm{f}dz1 - z3 - (z1 + \alpha)\left(\frac{Ed}{Ed} - \frac{Rs}{Ls}\right) + \alpha) \text{-------(5.13)}$$

$$\dot{V}3 = -\mathbf{f}vDCz^2 3 + z3z1 \qquad \text{---------------------(5.14)}$$

$$\dot{V}1 = -\mathbf{f}vDCz^2 3 - \mathbf{f}dz^2 1 \qquad \text{--------------------- (5.15)}$$

The proposed back stepping control structure for the dc-link voltage controller converter is shown in Fig. 5.2. From the top level view, a feed forward power measurement is added to the controller. The required input to ensure the stability of the dc link, Ψ1 (*t*), is generated

through the manipulation of the virtual control input *z*1. The PCC voltage, and the converter current. The details of how the implemented controller generates the reference vectors are presented in Fig. 4.5. As can be seen, the structure is fairly straightforward, compared, and has been implemented in commonly used synchronously rotating reference frame (de–qe) without sequence components extraction block or resonant compensator.

The control parameters for this type of controller are calculated as in (5.12) based on the desirable response of the associated modes: λi and λc for the current and dc-link voltage, respectively.

It is desirable to have high-power high-voltage converter based systems available during power system faults when they may be needed the most. Voltage-source converter (VSC)-based transmission systems have attractive potential features in terms of power flow control and stability of the network. A voltage-source converter (VSC) is the main building block for flexible ac transmission systems (FACTS) devices and, as of today HVDC technology up to several hundred megawatts. Although relatively low switching frequency operation of high-power converters is desirable, it makes them sensitive to power network imbalances when they may be needed the most.

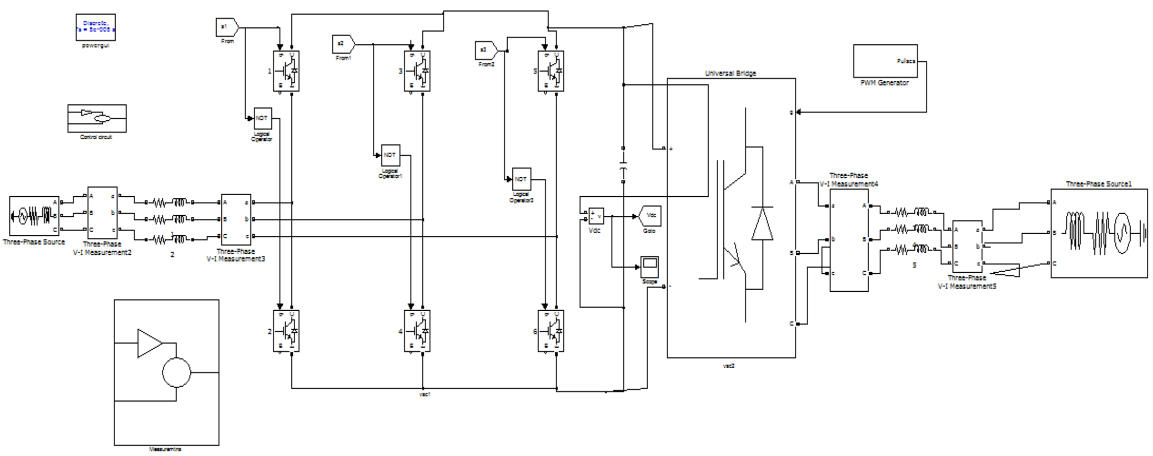
Today, the most promising market for HVDC technology is interconnection of the networks where the centers of the loads are located far from the points of connection. The problem of ac systems arises as the phase angle drifts and varies over a wide range with daily load changes. This phenomenon especially in a weak ac network along with the power line faults exacerbates the operation of HVDC systems. If the protection measures trip the converter system, it can take several fractions of an hour, depending on the size of the converter, to discharge the dc link and check the healthiness of the whole system. Hence, several practical methods have been proposed and implemented to keep a system operating under power system faults and disturbances. However, generally, less dependence on power semiconductor characteristics amounts to having more supplier possibilities for the VSC-based transmission.

The most important limiting factor of power semiconductors is their switching properties since they are usually optimized for the conduction intervals. Hence, high-power electronic converters are desired to operate with relatively low switching frequencies .The low switching frequency operation of VSC systems imposes control limitations in case of power system faults and disturbances when they may be needed the most.

This paper specifically proposes a control structure to improve the performance of high-power vector-controlled back-to-back VSC systems for conventional and emerging utility applications, the main improvement is to suppress the possible dc-link voltage fluctuations under power line faults and unbalanced conditions. The increasing emergence of VSC-based transmission is the result of development in semiconductor devices, power electronic circuits, control, and executive engineering. Previously, the lack of these developments had prohibited the VSC-based technology from being the first choice.

VI. MATLAB MODEL FOR PROPOSED CIRCUIT

6.1. BTB VSC for HVDC Applications (Start up Dynamic)



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BTB VSC systems in HVDC applications, represented in Fig.6.1. Are used for power flow control. One converter operates in *PQ* mode and the other one is responsible for compensating for the losses and ensuring a stable operation of the dc bus voltage, while it supports its reactive power demands. In vector-controlled VSC systems, reactive power is regulated independent of active power.

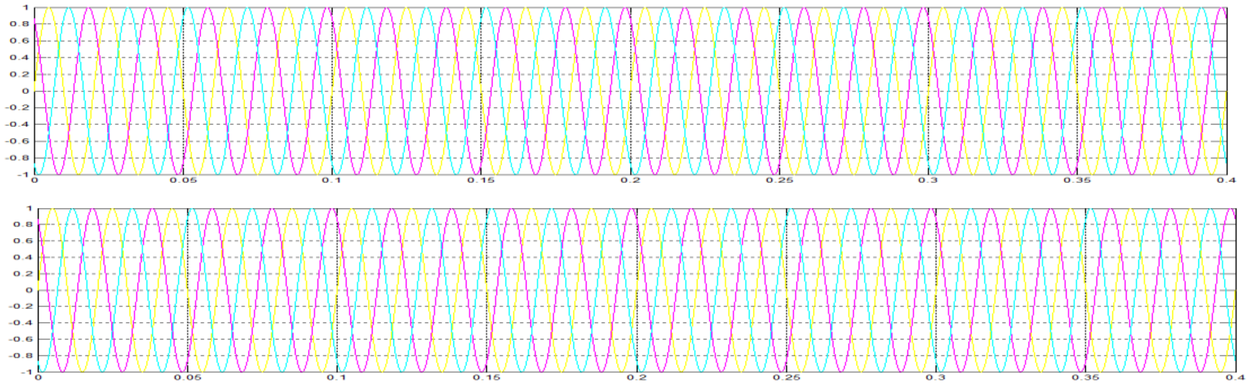


Fig.1. Output Voltages of Vsc1,Vsc2.

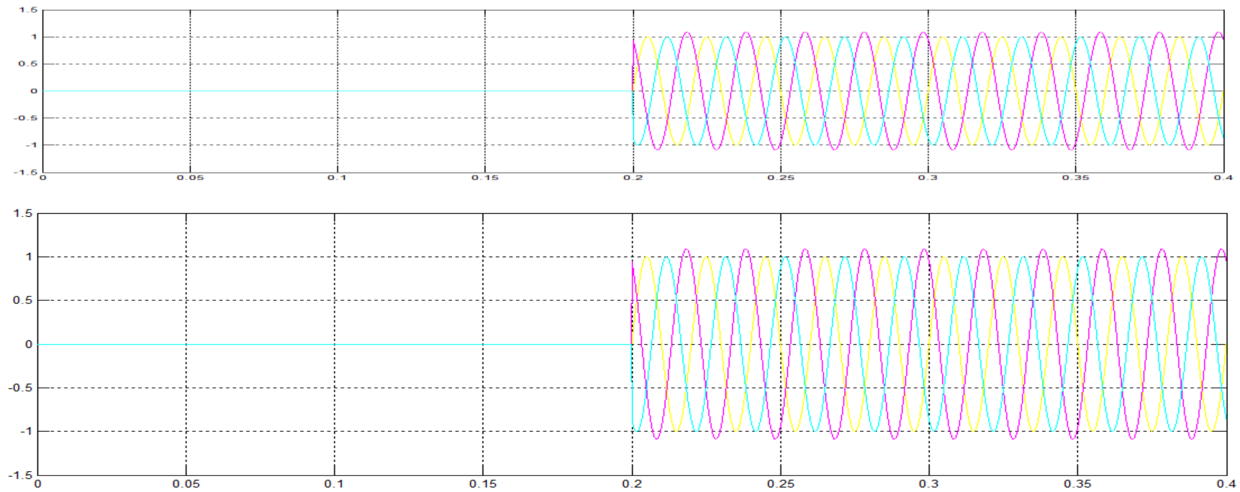


Fig.2. Three phase currents of VSC1,VSC2

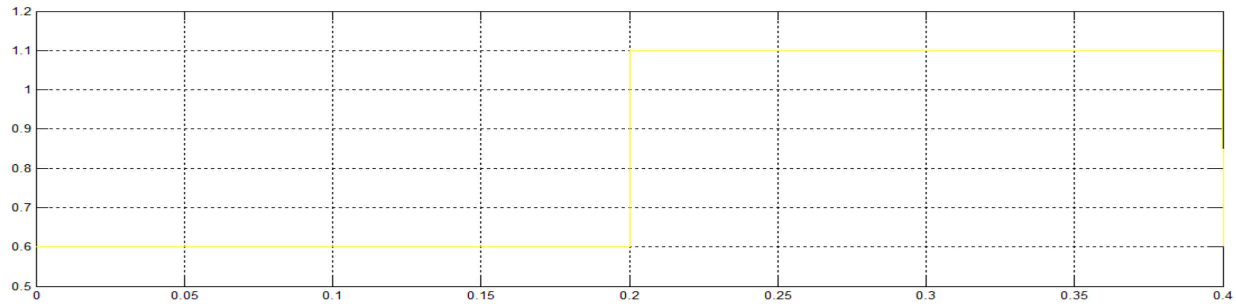
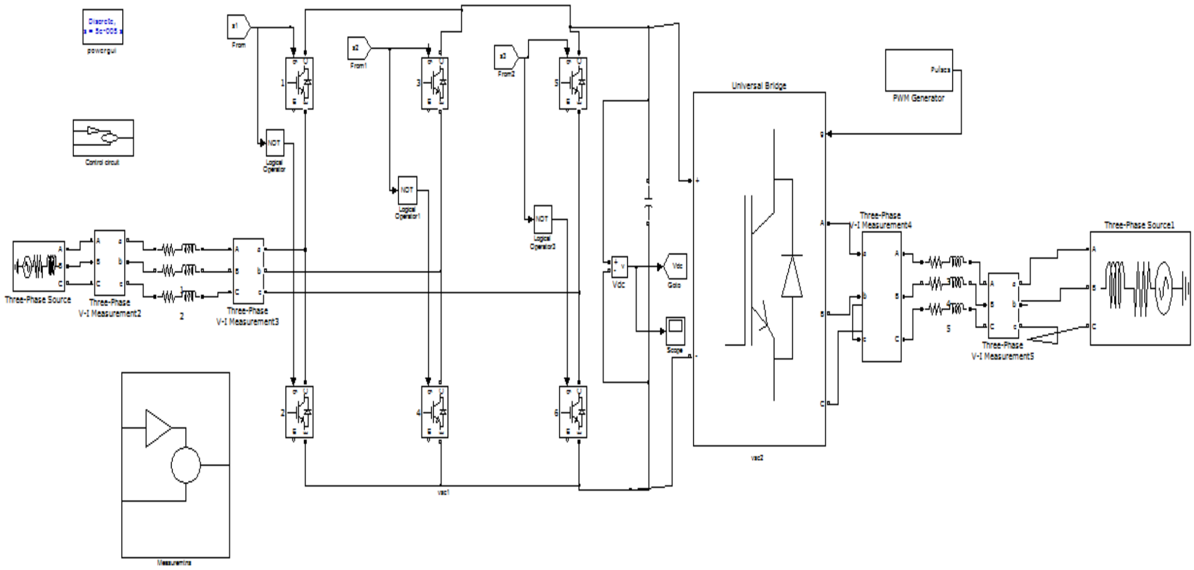


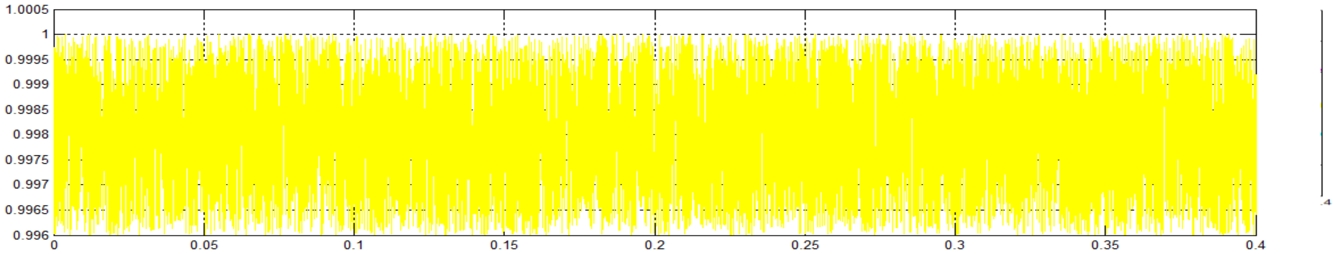
Fig.3. DC-link Voltage.

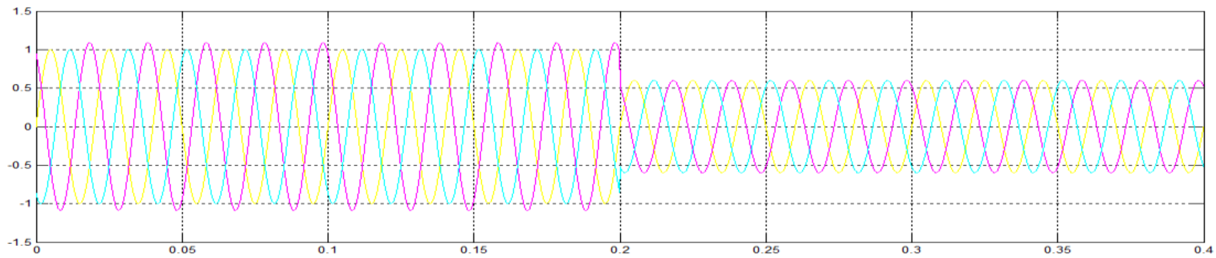
6.2. Proposed circuit for HVDC Application (Dynamic performance)

Fig.6.2 shows the dynamic performance of the VSC BTB system in response to a change power flow direction under balanced conditions. The system supplies 0.8 p.u. power, and the VSC1 (dc-link voltage controller) provides 0.2 p.u. capacitive and VSC2 (power flow controller) 0.6 p.u. inductive reactive power. As can be observed. The proposed controller for the BTB system, as well as the common control structures, operates satisfactorily. These values are considered in the following case studies to have consistency in the obtained result for unbalanced conditions.



Output Voltages of VSC1,VSC2.





Output Currents of VSC1,VSC2

DC link voltage.

6.3. The dynamic performance of the VSC BTB system under an unbalanced condition in the inverter side (power flow controller converter

The dynamic performance of the VSC BTB system under an unbalanced condition in the inverter side (power flow controller converter) is presented in Fig.6.3. The unbalanced system is represented by a 50% voltage drop in phase A of the inverter side PCC voltages Vabc 2 which can be considered as a fault near the inverter station. The fault remains for six cycles. As can be observed, the dc-link voltage remains practically stiff, and a harmonic measurement of the dc-link voltage for the second and fourth harmonics shows a satisfactory level of compensation. This mode of operation is mainly of interest in the literature.

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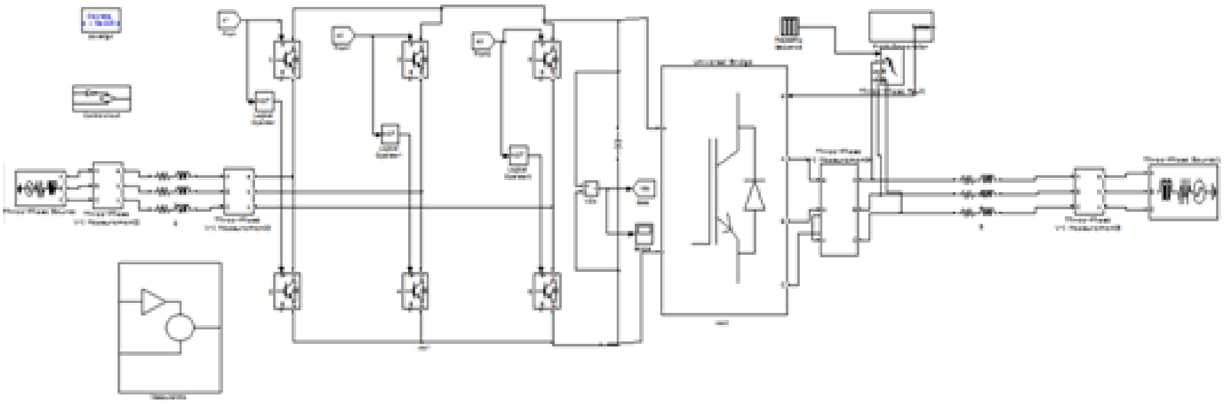
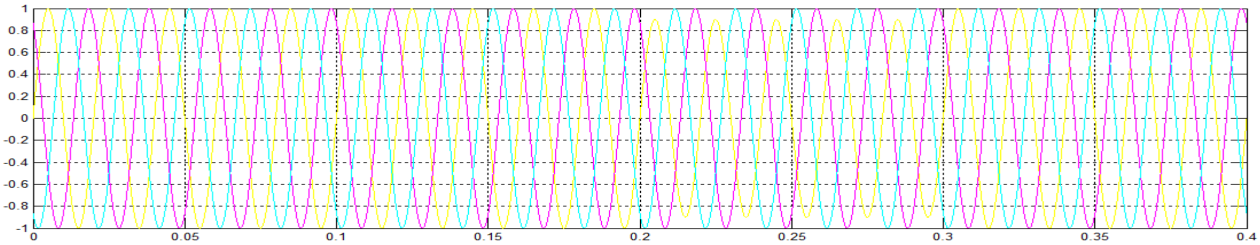
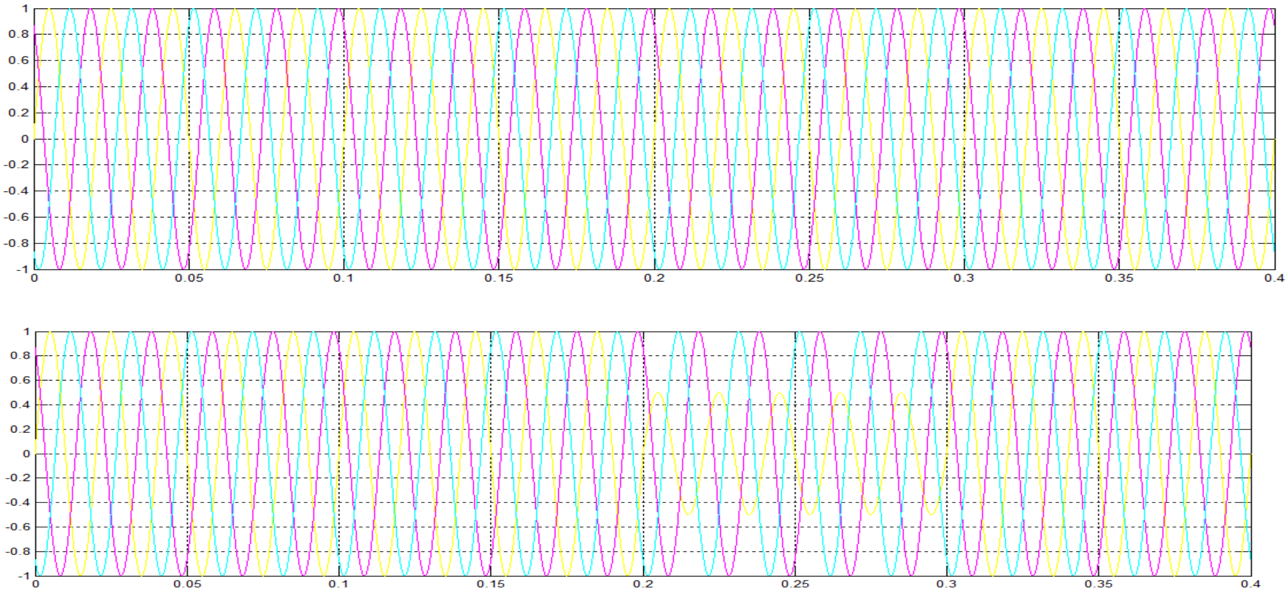


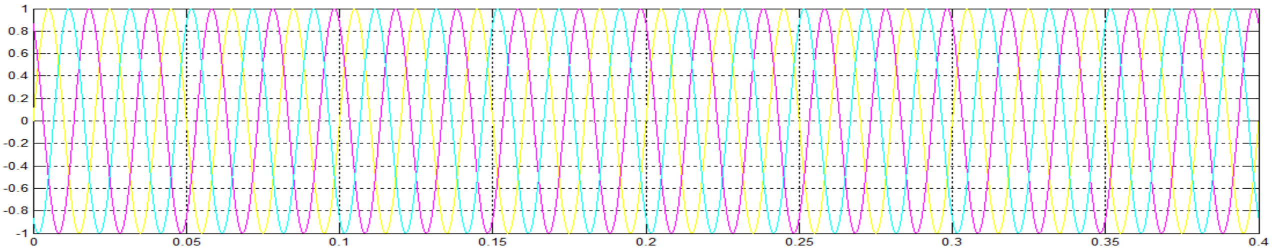
Proposed circuit under inverter side phase A fault

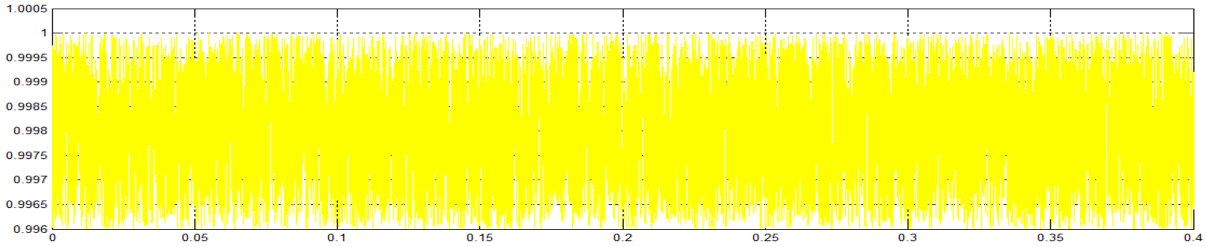


Output voltages of VSC1, VSC2.



Output currents of VSC1,VSC2.

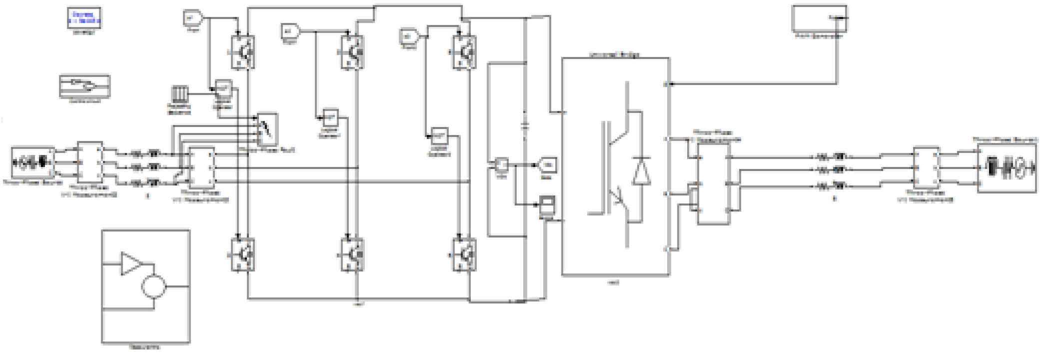




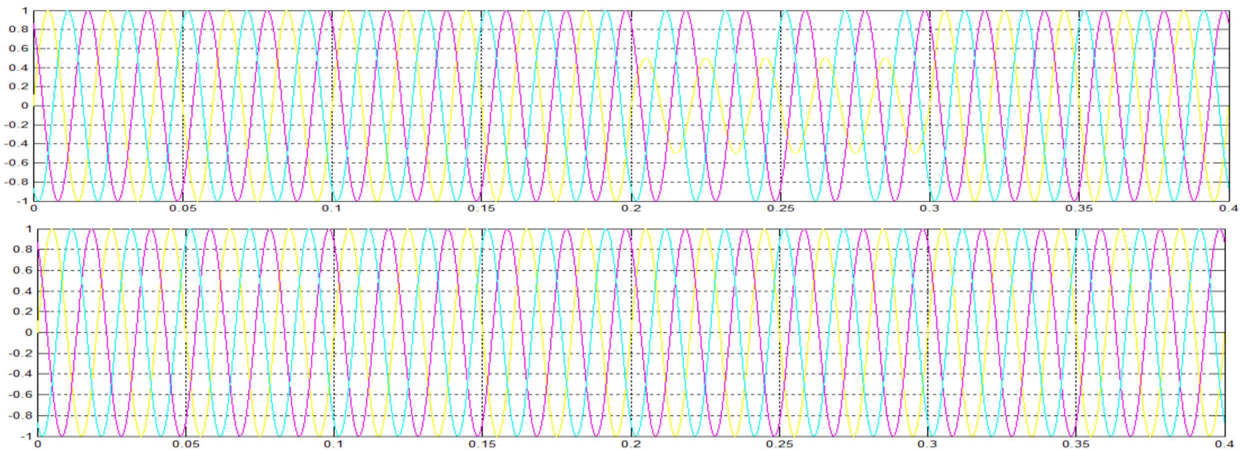
DC link voltage.

6.4. The dynamic performance of the BTB system when a 50% voltage drop occurs in phase A of the rectifier side (dc-link voltage controller).

Fig.6.4 presents the dynamic performance of the BTB system when a 50% voltage drop occurs in phase A of the rectifier side (dc-link voltage controller). Due to the voltage drop, the rectifier carries higher currents to maintain the load power and regulate the dc bus voltage. It can be seen that the dc-link voltage has a minor change of about 1% p.u. and the effect of negative sequence power is reduced to 1.5% p.u. presented in the dc-link voltage. It can also be observed that the inverter current is hardly affected by the dynamics of the dc link under the unbalanced condition.



Proposed circuit under phase A fault at rectifier side.



Output voltages of VSC1,VSC2.

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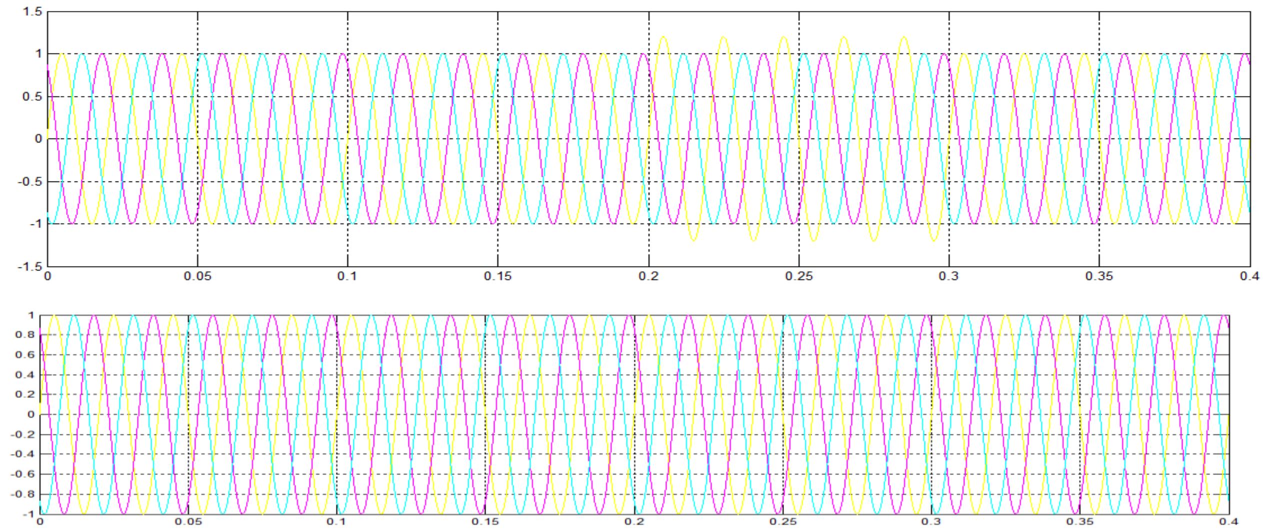
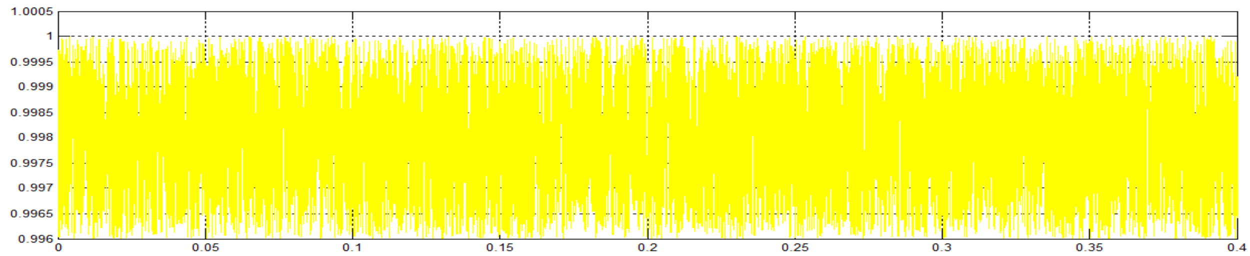


Output currents of VSC1,VSC2.



6.5. The dynamic performance of the VSC BTB system in HVDC applications while the dc-link controller is operated as an inverter and the power flow controller as rectifier.

This mode of operation may not be practical in HVDC power transactions and it is presented to combine the problem and address the dynamics. In Fig.6.5, the unbalanced system is represented by a 50% voltage drop in phase A of the PCC voltages Vabc 1. The fault remains for six cycles. As can be observed the dc-link voltage remains practically stiff, and harmonic measurement of the dc-link voltage for the second and fourth harmonics shows a satisfactory level of compensation. The inverter currents change (increase in phase A) to compensate for the unbalanced power flowing into the system; however, it remains within the safe operating area of the switches.

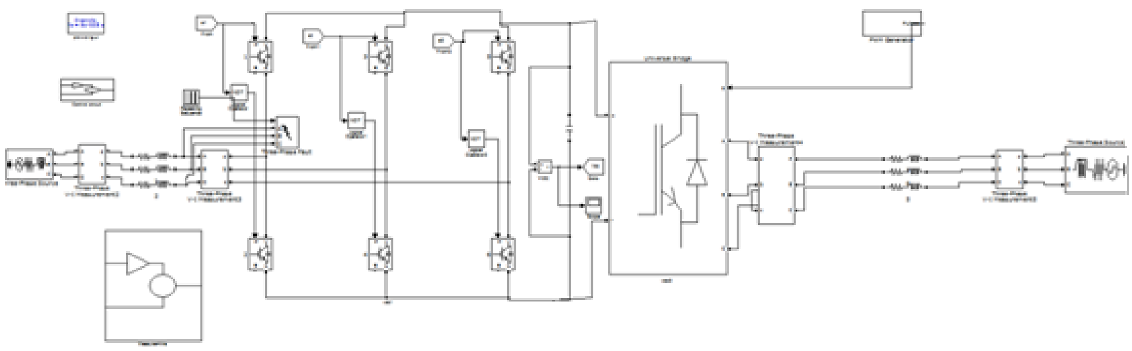


Fig6.24.. Proposed circuit for change of power flow.

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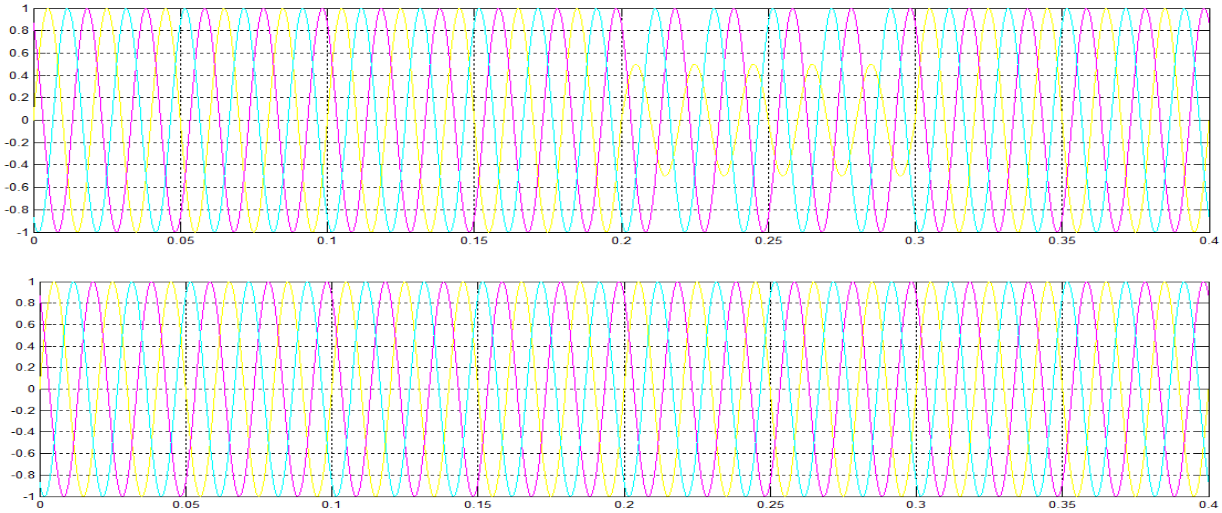

Fig.6.25.Output voltages of VSC1,VSC2.

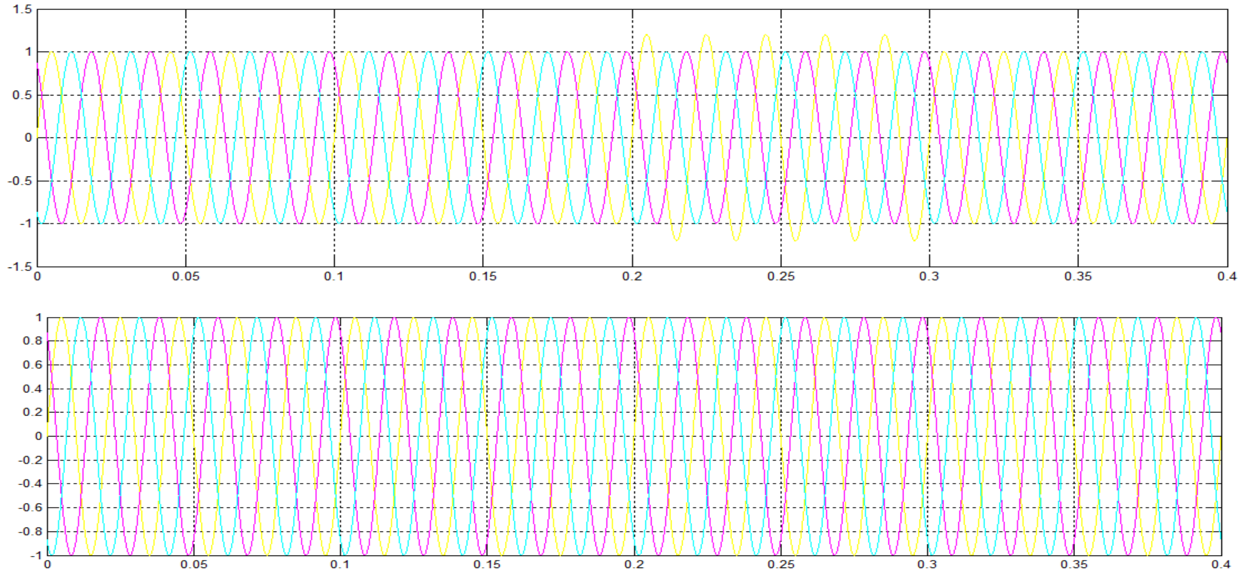

Fig.6.26.Output currents of VSC1,VSC2.

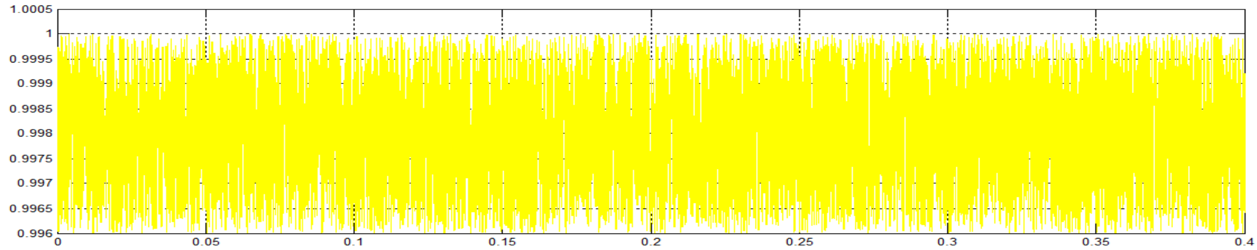

Fig.6.27. DC link voltage.

6.6. Voltage drop in phases B and C of the power flow controller side

The system performance under more severe imbalances is shown in Fig.6.6 represented by a 50% and 90% voltage drop in phases B and C of the power flow controller side, respectively.

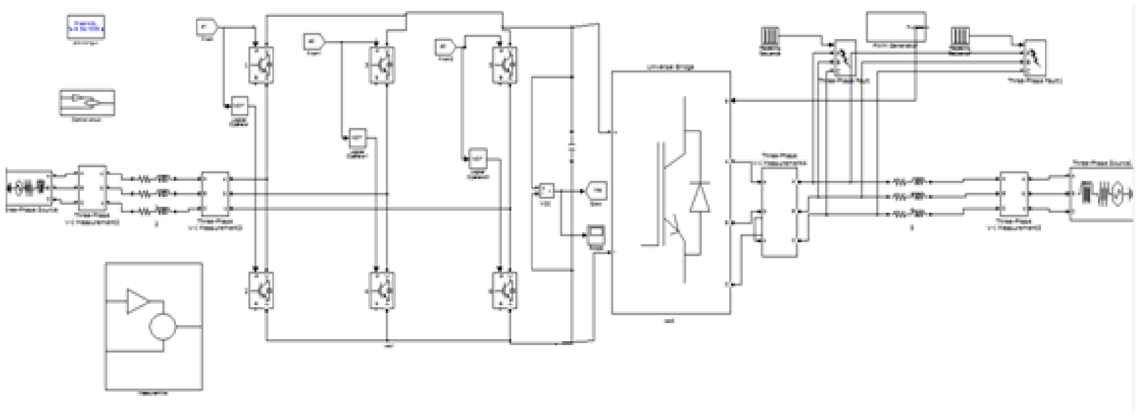

Fig.6.28. Proposed circuit.

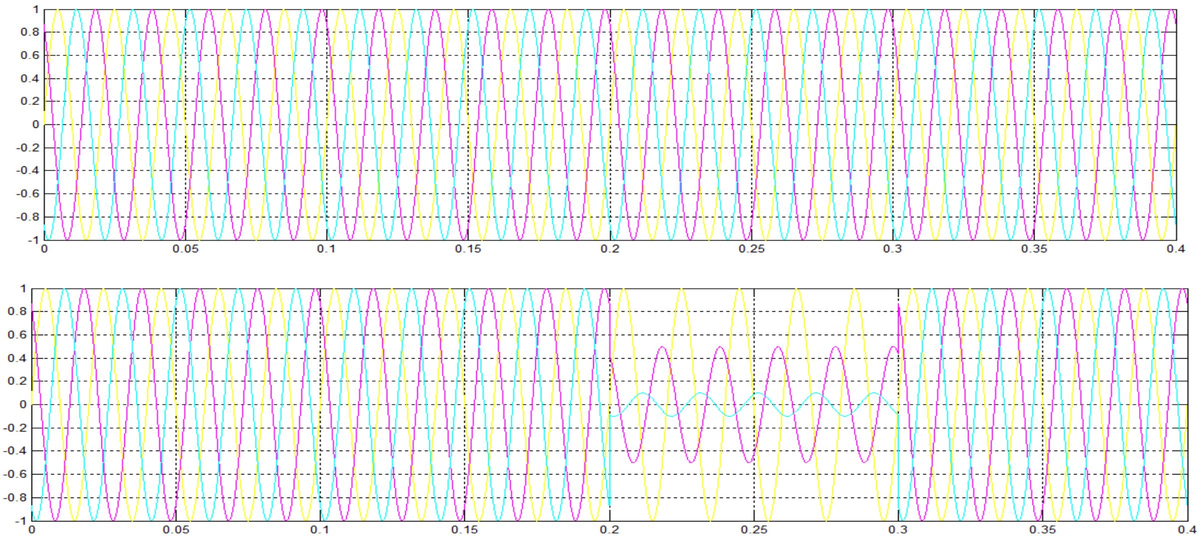

Fig.6.29.Output voltages of VSC1,VSC2.

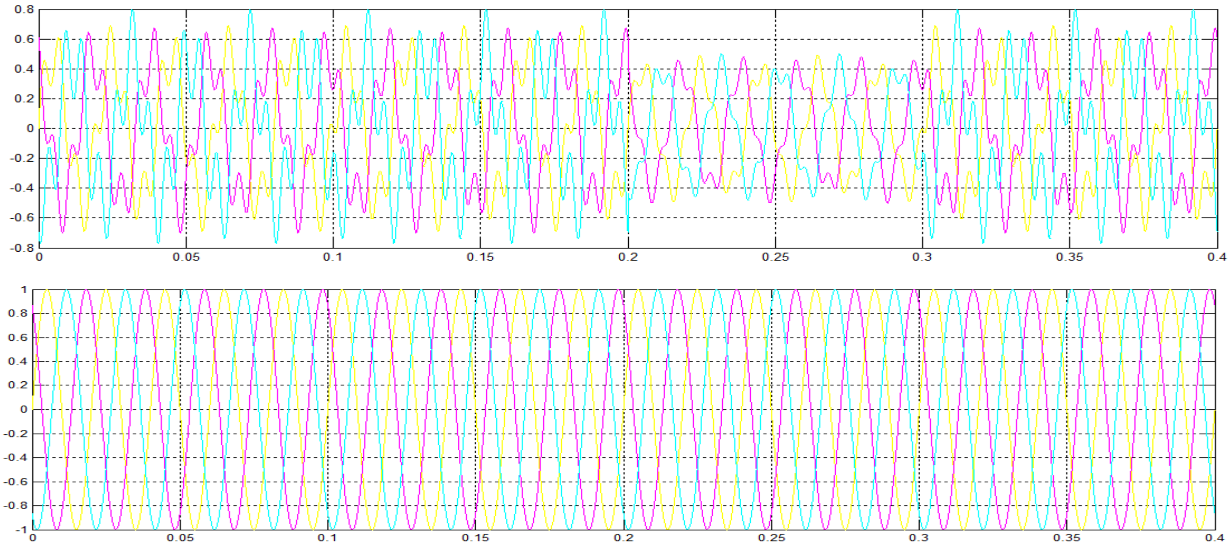

Fig.6.30.Output currents of VSC1,VSC2.

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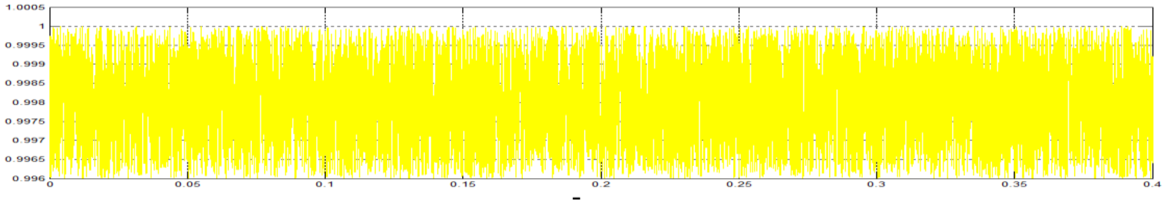

Fig.6.31.DC link voltage.

VII. CONCLUSION

This paper has addressed the dc-link voltage control issues for vector-controlled VSC-based transmission systems under power system disturbances. Having analyzed the current state-of-the-art methods of mitigating the dc-link voltage fluctuations under grid faults and disturbances, we have proposed a control structure in the commonly used d-q synchronous reference frame. The proposed structure obviates the need for the sequence extraction blocks or the resonant compensators. Therefore, there is no diminishing bandwidth factor. The scheme, however, utilizes the interaction of the converters, the load, bus voltage, and their derivatives to compensate for the phase delay in the current regulator. The proposed scheme was explained through a back stepping control method in which its Lyapunov-based structure ensures the stability of the system. The results verification of the controller attained less than 1% dc-link voltage deviation under most common faults and disturbances, demonstrating the applicability and effectiveness of the proposed scheme for transmission system denoted as HVDC application.

Based on the results obtained in different case studies, the effectiveness of the proposed controller is shown for HVDC applications under normal and unbalanced conditions. In other words, the deficiency of the high-power VSCs in terms of control bandwidth is improved through a high-bandwidth control architecture that does not require any sequence extraction or any diminishing bandwidth factors. From the results obtained, it can be concluded that the proposed control scheme is effective in maintaining a robust dc-link voltage even under unbalanced grid conditions.

As can be observed, the dc-link voltage remains practically stiff, and harmonic measurement of the dc-link voltage for the second and fourth harmonics shows a satisfactory level of compensation under this severe fault case.

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