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A Contemporary Custom Power Device Based on Dual Angle Control to Mitigate System Faults

G. Sriram Prasad
Department of EEE,
CMRCET,
Kandlakoya(v), Hyderabad.

G. Devadas
Department of EEE,
CMRCET,
Kandlakoya(v), Hyderabad.

K.Soujanya
Department of EEE,
CMRCET,
Kandlakoya(v), Hyderabad.

Abstract:

The main purpose of introducing FACTS devices to power systems is to increase stability and transmission capability. The static synchronous compensator (STATCOM) belonging to the family of flexible alternating current transmission system (FACTS) devices based on the voltage source converter (VSC) is a regulating device used in alternating current transmission systems. In recent years, angle-controlled STATCOMs have been deployed by utilities for the purpose of transmission system voltage regulation, voltage stability improvement and increasing operational functionality.

Despite the superior feature on voltage waveform quality and efficiency, the practical angle-controlled STATCOMs suffer from the over-current (and trips) and possible saturation of the interfacing transformers caused by negative sequence current during unbalanced conditions and faults in the utility. This paper specifically proposes a control structure to improve theangle-controlled STATCOMs performance under unbalanced conditions and faults.

The main improvement is a substantial decrease in the negative sequence current and DC-link voltage oscillations and output voltage THD under power system faults by the proposed control. The proposed control structure is designed based on adding appropriate oscillations to the conventional Angle-controller output that is the control angle by which the VSC voltage vector leads/lags the line voltage vector.

Since this control structure uses two angles for controlling the VSC output voltage, it is called Dual Angle Control (DAC).The simulation results verify the validity of the proposed control structure under unbalanced system conditions and faults.

Index Terms:

STATCOM, line-frequency-switched inverter, angle-control, dual angle control, fault operation.

I. INTRODUCTION :

In recent year's energy, environment, right-of-way, and cost problems have delayed the construction of both power stations and new transmission lines, while the demand for electric power has continued to grow in many countries. This situation has spurred interest in providing already existing power systems with greater operating flexibility and better utilization, thus having led to the concept of flexible ac transmission systems (FACTS). The main purpose of introducing FACTS devices to power systems is to increase stability and transmission capability. The static synchronous compensator (STATCOM) belonging to the family of flexible alternating current transmission system (FACTS) devices based on the voltage source converter (VSC) is a regulating device used in alternating current transmission systems.

The Voltage Source Converter (VSC) based STATCOM is used for voltage regulationin Transmission and distribution systems. Unlike the PWM-Controlled STATCOMs, Angle-controlled STATCOMs are switched at line frequency to achieve lower system losses. In recent years, angle-controlled STATCOMs have been deployed by utility owners for the purpose of voltage regulation, voltage stability improvement and increasing operational functionality. The operation of the STATCOMs and shunt converter in the UPFC mode is based on angle-controller strategy. Despite the superior feature on voltage waveform quality and efficiency, the practical angle-controlled STATCOMs suffer from the over-current (and trips) and possible saturation of the interfacing transformers caused by negative sequence current during unbalanced conditions and faults, when the VAR support is needed the most. It is important to note that solutions proposed in the literature to improve the PWM based VSC performance under unbalanced conditions are not applicable to angle-controlledSTATCOMs. The main motivation to use Angle-controlled STATCOM is to obtain higher waveform quality of voltage with lower losses compared to PWM VSC. This paper presents a new control structure for high power angle-controlled STATCOMs during normal and fault conditions. The only control input in the angle-controlledSTATCOM is phase angle difference between VSC and AC bus instantaneous voltage vector (α) [1] . In the proposed controller,αissplit into twoparts,αdc andαac .

The DC part (αdc) which is the conventional angle-controller output is in charge of controlling the positive sequence VSC output voltage.The oscillating part (αac) controls the DC-link voltage oscillations with twice the line frequency to generate required fundamental negative sequence voltages at the VSC output terminals to limit the negative sequence current. Since this control scheme uses two angles (αdc and αac) as control inputs, it is called Dual Angle Control (DAC). The Dual Angle Control stabilizes the STATCOM DC bus during power system faults, and therefore allows the STATCOM to continue operation without tripping.

In this paper, we address the issue of limiting the STATCOM negative sequence current, and thus the resulting DC-link voltage oscillations, in high-power angle-controlledSTATCOMs, to enable the STATCOM to operate without tripping in the presence of power system faults and AC-system voltage unbalances. We give an analysis of STATCOM unbalanced operation, followed by a description of the proposed dual angle control method. The proposed STATCOM is modelled using MATLAB/SimPowerSystems (SPS) tool boxes and the developed model is used to simulate its performance.

II. BASIC STRUCTURE AND CONTROL SCHEMES OF STATCOM :

Fig. 1 shows the basic structure of a STATCOM connected to a load bus in a power system where Rp represents the 'ON' state resistance of the switches including transformer leakage resistance, Lp is transformer leakage inductance and the switching losses are taken into account by a shunt dc-side resistance Rdc.

A VSI resides at the core of the STATCOM. It generates a balanced and controlled three-phase voltage Vp. The voltage control is achieved by firing angle control of the VSI.

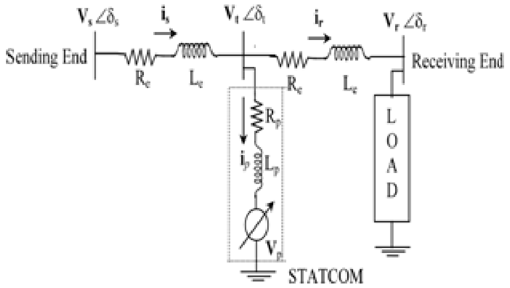

Fig.1.Basic structure of STATCOM connected to a load bus in a power system.

Under steady state, the dc-side capacitor possesses fixed voltage Vdc and there is no real power transfer, except for losses. Thus, the ac-bus voltage remains in phase with the fundamental component of Vp. However, the reactive power supplied by STATCOM is either inductive or capacitive depending upon the relative magnitude of fundamental component of Vp with respect to Vt. If Vt >Vpthe VSI draws reactive power from the ac-bus whereas if Vt<Vp, it supplies reactive power to the ac-system.Fig.2 shows the equivalent circuit of a six-pulse STATCOM connected to a load bus in a power system.

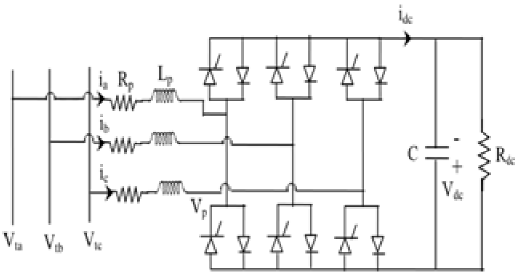

Fig.2 Equivalent circuit of a six-pulse STATCOM connected to a load bus in a power system.

2.1 CONTROL SCHEMES OF STATCOM:

All the VSCs, which are building block of FACTS devices, regardless of their topology can be divided into two types depending on their control methods. One type is vector controlled or PWM-based converter. However, this type of inverter may be uneconomical for many transmission level FACTS devices due to the high switching losses of the PWM VSCs.

A. Description of Angle-Controlled STATCOM-Structure:

The other type of inverter is based on controlling only the angle of the output voltage. It has been shown in [1] that by a slight change of the inverter output voltage angle for a controlled time, the inverter is able to provide inductive/capacitive reactive power. Basically by controlling the α toward the positive/negative direction , for a controlled time, the DC-link voltage is driven lower/higher and therefore the VSC output voltage decreases/increases accordingly[1] .Since angle α is the only control input in this control strategy, it is called angle control. Control architecture of the conventional angle controller STATCOM is illustrated in Fig.3.

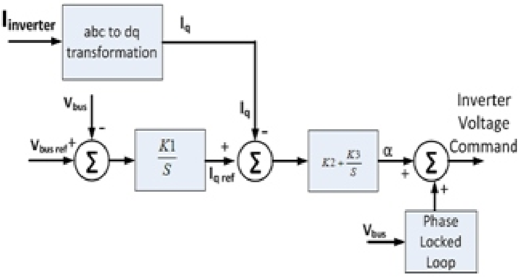

Fig.3. Control structure of a STATCOM working with vector controlled inverter.

High-quality output voltage of the angle-controlled STACOM is provided by multi-pulse inverters. 24-pulse and 48-pulse inverters are commonly used for this kind of STATCOMs at the transmission level since the output voltage THD is 1-2% with low overall converter losses. The performance of this STATCOM under normal operating condition and variable instantaneous reactive current (Iq) references is illustrated in Fig. 4.

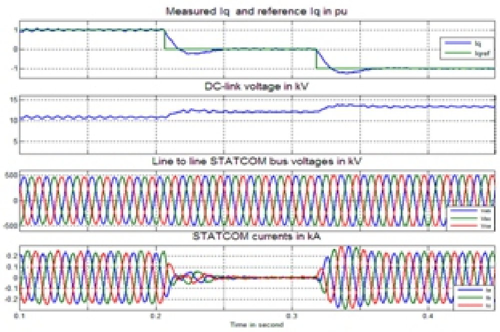

Fig.4. Angle-controlledSTATCOM performance with two different instantaneous reactive current (Iq) references

III. ANALYSISOFVSCUNDERUNBALANCEDOPERATINGCONDITION:

Symmetrical component are most commonly used for analysis of three-phase unbalanced electrical systems. In this method, a set of unbalanced three phase phasors is split into two symmetrical positive and negative sequences and one zero sequence component. Based on this theory, tie line currents of the STATCOM in Fig. 2 under fault condition will be as:

$$i_a = i_a^+ + i_a^- + i_a^0 \qquad (1)$$

$$i_a = i^+ \sin(\omega t + \theta_i^+) + i^- \sin(\omega t + \theta_i^-) + i^0 \sin(\omega t + \theta_i^0) \qquad (2)$$

$$i_b = i^+ \sin\left(\omega t + \theta_i^+ - \frac{2\pi}{3}\right) + i^- \sin\left(\omega t + \theta_i^- + \frac{2\pi}{3}\right) + i^0 \sin(\omega t + \theta_i^0) \qquad (3)$$

$$i_c = i^+ \sin\left(\omega t + \theta_i^+ + \frac{2\pi}{3}\right) + i^- \sin\left(\omega t + \theta_i^- - \frac{2\pi}{3}\right) + i^0 \sin(\omega t + \theta_i^0) \qquad (4)$$

Since there is no path for neutral current to flow in three wire system, the zero sequence component is ignored throughout this paper. As it was mentioned earlier, in the angle-controlled STATCOM the only control input is angle α which is always applied identically to all three phases of the inverter. Therefore, the switching function for an angle-controlledSTATCOM is always symmetric and by neglecting all the harmonics except the fundamental, (which is a fair assumption for a 24 and 48-pulse inverter due to output voltage THD typically less than 1%), the switching function for phase a, b, and c can be represented as:

$$s_a = K \sin(\omega t + \alpha) \qquad (5)$$

$$s_b = K \sin\left(\omega t + \alpha - 2\frac{\pi}{3}\right) \qquad (6)$$

$$s_c = K \sin\left(\omega t + \alpha + 2\frac{\pi}{3}\right) \qquad (7)$$

WhereK is the factor for the inverter which relates the DCside voltage to the amplitude of the phase to neutral voltage at the inverter AC-sideterminals,andαistheangle bywhichthe inverter voltage vector leads/lags the line voltage vector. Then the inverter terminal fundamental voltage is calculated as:

$$v_a = K\, v_{DC} \sin(\omega t + \alpha) \qquad (8)$$

$$v_b = K\, v_{DC} \sin\left(\omega t + \alpha - 2\frac{\pi}{3}\right) \qquad (9)$$

$$v_c = K\, v_{DC} \sin\left(\omega t + \alpha + 2\frac{\pi}{3}\right) \qquad (10)$$

The interaction between the fundamental frequency inverter switching function and the negative sequence component of the current, produces 2nd harmonic oscillations on the DC-link voltage and current . Therefore general expression of DC-link voltage during unbalanced condition becomes.

$$v_{DC} = V_{dc} + V_{dch2}\cos(2\omega t + \theta_v^{dc}) \qquad (11)$$

where is the average value and is the amplitude of the 2nd harmonic oscillations of DC-Link voltage.Substituting (11) in (8)-(10), the inverter output voltages when the DC-link voltage is distorted by 2nd harmonic oscillations due to the unbalanced AC system are calculated as:

$$v_a = \mathrm{K}\,V_{dc}\sin(\omega t + \alpha) + \frac{KV_{dch2}}{2}\sin(3\omega t + \alpha + \theta_v^{dc}) + \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \theta_v^{dc}) \qquad (12)$$

$$v_b = \mathrm{K}\,V_{dc}\sin\left(\omega t + \alpha - 2\frac{\pi}{3}\right) + \frac{KV_{dch2}}{2}\sin\left(3\omega t + \alpha + \theta_v^{dc} - 2\frac{\pi}{3}\right) + \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \theta_v^{dc} - 2\frac{\pi}{3}) \qquad (13)$$

$$v_c = \mathrm{K}\,V_{dc}\sin\left(\omega t + \alpha + 2\frac{\pi}{3}\right) + \frac{KV_{dch2}}{2}\sin\left(3\omega t + \alpha + \theta_v^{dc} + 2\frac{\pi}{3}\right) + \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \theta_v^{dc} + 2\frac{\pi}{3}) \qquad (14)$$

Equations (12)-(14) show that the interaction between switching function and the DC-link voltage 2nd harmonic oscillations generates fundamental negative sequence voltage at the VSC output terminals. Basically, the unbalanced ACsystem conditions can be emulated by postulating a set of negative sequence voltage source in series with STATCOM tie line [2].The basic idea of the Dual Angle Control strategy is to generate required fundamental negative sequence voltage vector at the VSC output terminals to attenuate the effect of postulated negative sequence bus voltage. The generated negative sequence voltage, results in reduction of the negative sequence current seen by the STATCOM under fault conditions. It is important to note that interaction between switching function and the DC-link voltage 2nd harmonic oscillations also generates 3rd harmonic voltage at the VSC output terminals. This 3rd harmonic voltage is positive sequence and phase a, b, and c are 120 degree apart. Basically the negative sequence current flow due to unbalanced ACsystem condition generates the 2nd harmonic oscillations on the DC-link voltage which will be reflected as fundamental negative sequence voltage and 3rd harmonic voltage at the VSC terminals.

Similar to the fundamental negative sequence voltage, the amplitude of this 3rd harmonic voltage is decided by the DC-link voltage 2nd harmonic oscillations. This paper will show that by controlling 2nd harmonic oscillations on the DC-link voltage, the negative sequence current will reduce significantly. Decreased negative sequence current will inherently reduce the DC-link voltage 2nd harmonic oscillations. Reduction in DC-link voltage 2nd harmonic oscillations results in decreasing the 3rd harmonic voltage and therefore current at STATCOM tie line.

IV. PROPOSED CONTROL STRUCTURE DEVELOPMENT :

A. Derivation of STATCOM equations in the negative synchronous frame :

As discussed in the previous section, STATCOM voltage and current during unbalanced conditions can be calculated by postulating a set of negative sequence voltage in series with STATCOM tie line as shown in Fig.5.

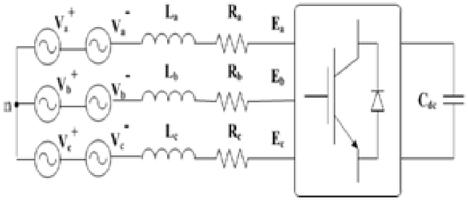

Fig.5.STATCOM equivalent circuit with series negative sequence voltage sources.

As discussed earlier, negative sequence current at STATCOM tie line generates 2nd harmonic oscillations at the DC-link voltage. These 2nd harmonic oscillations will be reflected as negative sequence voltage at STATCOM terminals as calculated in (12)-(14). Assuming 2ndharmonic oscillation at DC-link voltage as:

$$V_{dch2}\cos(2\omega t + \alpha') \qquad (15)$$

then reflected negative sequence voltages at STATCOM terminal are calculated as in (16)-(18).

$$e_a^- = \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \alpha') \qquad (16)$$

$$e_b^- = \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \alpha' - \frac{2\pi}{3}) \qquad (17)$$

$$e_c^- = \frac{KV_{dch2}}{2}\sin(-\omega t + \alpha - \alpha' + \frac{2\pi}{3}) \quad (18)$$

The derivative of STATCOM tie line negative sequence currents with respect to time are calculated as in (19)-(21).

$$\frac{di_a{}^-}{d_t} = \frac{-R}{L} i_a{}^- + \frac{(e_a{}^- - V_a{}^-)}{L} \quad (19)$$

$$\frac{di_b{}^-}{d_t} = \frac{-R}{L} i_b{}^- + \frac{(e_b{}^- - V_b{}^-)}{L} \quad (20)$$

$$\frac{di_c{}^-}{d_t} = \frac{-R}{L} i_c{}^- + \frac{(e_c{}^- - V_c{}^-)}{L} \quad (21)$$

Transformation from abc to negative synchronous frame is defined as:

$$f_{dq}^- = T(-\omega t) f_{abc}^- \quad (22)$$

where

$$T(-\omega t) = \quad (23)$$

$$\frac{2}{3}\begin{bmatrix} \cos(-\omega t) & \cos(-\omega t - \frac{2\pi}{3}) & \cos(-\omega t + \frac{2\pi}{3}) \\ -\sin(-\omega t) & -\sin(-\omega t - \frac{2\pi}{3}) & -\sin(-\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

and ωt is the STATCOM ac-bus phase locked loop output.

Fig.6. illustrates the instantaneous negative sequence STATCOM bus (v^-)and inverter output voltage (e^-) in the negative synchronous frame. Vector v^- is assumed to have an arbitrary angle of Θ'.

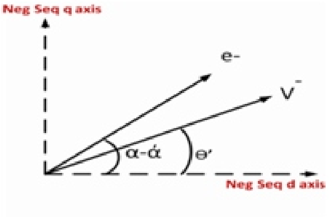

Fig.6.STATCOM instantaneous vectors in the negative synchronous frame.

d and q components of these two vectors are calculated as:

$$e_d^- = |e^-|\cos(\alpha - \alpha') = \frac{KV_{dch2}}{2}\cos(\alpha - \alpha') \quad (24)$$

$$e_q^- = |e^-|\sin(\alpha - \alpha') = \frac{KV_{dch2}}{2}\sin(\alpha - \alpha') \quad (25)$$

$$v_d^- = |v^-|\cos(\theta') \quad (26)$$

$$v_q^- = |v^-|\sin(\theta') \quad (27)$$

Transforming equation (19)-(21) based on (23), we find:

$$\frac{d}{dt} i_d^- = \frac{-R}{L} i_d^- - \omega i_q^- + \frac{K}{2L} V_{dch2}\cos(\alpha - \alpha') - \frac{1}{L} v_d^- \quad (28)$$

$$\frac{d}{dt} i_q^- = \frac{-R}{L} i_q^- + \omega i_d^- + \frac{K}{2L} V_{dch2}\sin(\alpha - \alpha') - \frac{1}{L} v_q^- \quad (29)$$

Equation (28) and (29) describe the dynamics of the VSC AC side negative sequence current, in terms of negative synchronous frame variables and 2nd harmonic oscillations of the DC-link voltage. These equations show that the dynamics of STATCOM tie line negative sequence current d and q components(i_d^- ,i_q^-)are related to the phase and amplitude of the DC-link voltage 2nd harmonic oscillations.

B. Control input to control the negative sequence current :

As discussed earlier, Dual Angle Control strategy is based on generating required fundamental negative sequence voltage vector at the VSC output terminals to attenuate the effect of postulated negative sequence bus voltage under fault conditions and to limitthe negative sequence current. The required negative sequence voltage vector is obtained by controlling the 2nd harmonic DC-link voltage oscillations. This part of the paper shows that DC-link voltage 2ndharmonic oscillations are controlled by adding appropriate oscillations to the conventional angle controller output i.e. angle α. It was mentioned earlier that α is the only control input for the anglecontrolled STATCOM. α is a control angle that has a pulse type characteristic in the normaloperation. In steady state α is zero. Transiently t moves toward the positive or negative direction to decrease or increase the DC-link voltage and then goes back to zero. Figure 7 illustrates the 2nd harmonic DC-link voltage oscillations generated by introducing 2nd harmonic oscillations to the α in both capacitive and inductive mode of operations.

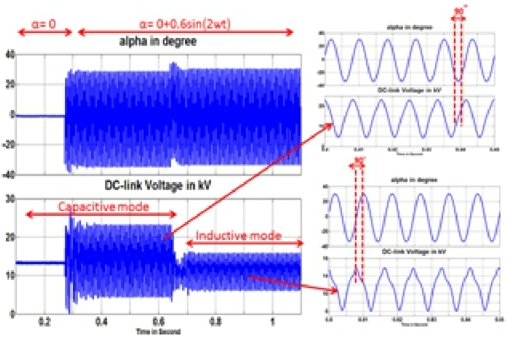

Fig.7. DC-link voltage 2nd harmonic oscillations generated by introducing 2nd harmonic oscillations to theα in both capacitive and inductive operation modes.

Initially the STATCOM is working in capacitive mode with steady state α of 0°. At around t=0.3 second, 2nd harmonic oscillation of 0.6sin (2t) radian is added to α. These oscillations generate 90° leading 2nd harmonic oscillations on the DC-link voltage. At around t=0.7 second, STATCOM switched to inductive mode and as can be observed, DC-link voltage oscillations amplitude decreases but it is still leads the α oscillations by 90°. This concept of 90° phase shift between DC-link voltage and α 2nd harmonic oscillations has been used in the Dual Angle Controller. The application of this concept to develop the DAC has been discussed in details in the following part and appendix (A)

C. Proposed Dual AngleControl structure :

In the proposed controller, angle α is split into two parts, αdc and αac. The proposed control structure is shown in Fig. 8. The angle αdc is the output of the positive sequence controller which is the same as conventional angle controller.

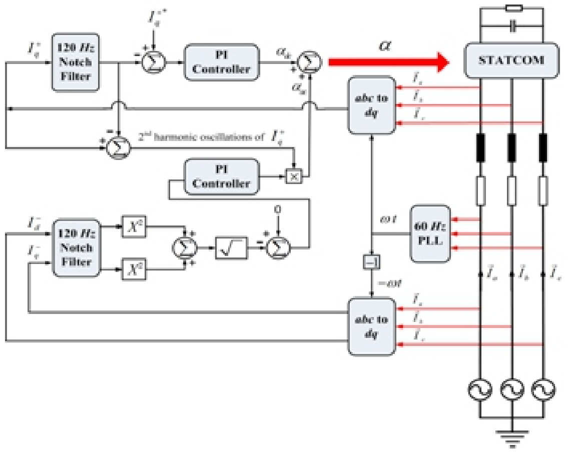

Fig.8. Dual Angle Control structure

Rejection notch filter at double the line frequency has been added to the measured current in synchronous frame to isolate the positive sequence controller from the negative sequencesignals. The output of the negative sequence controller is αac. The angle αac is the 2nd harmonic oscillations with appropriate phase and amplitude to generate the required negative sequence voltage vector at the VSC terminals to attenuate the effect of the postulated negative sequence bus voltage under fault conditions.

The generated negative sequence voltage results in reduction of the negative sequence current seen by the STACOM. Like the positive sequence controller, sequence extraction is implemented using rejection notch filters. The αac should be properly filtered such that it contents only 2nd harmonic oscillations otherwise it will generate higher order harmonics oscillations on the DC-link voltage which will be reflected as higher order harmonic voltage on the AC-side. It was discussed earlier that 2nd harmonic oscillations on the DC- link voltage does not affect the fundamental inverter output voltage and all the other harmonics (excluding the 3rd and fundamental negative sequence voltage) remain almost unchanged. The phase of the αac is coming from the2nd harmonic oscillations of the q-axis component of the tie line current in the positive synchronous frame when system is unbalanced. The negative sequence current appears as 2nd harmonic oscillations in the q-axis component of the line current in positive synchronous frame as calculated in (30).

$$\frac{2}{3}\begin{bmatrix} i^- \sin(-\omega t + \theta_i^-) \\ i^- \sin\left(-\omega t + \theta_i^- - \frac{2\pi}{3}\right) \\ i^- \sin\left(-\omega t + \theta_i^- + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} =$$

$$i^- \cos(-2\omega t + \theta_i^- + \pi) = i^- \cos(2\omega t - \theta_i^- + \pi) \qquad (30)$$

V. SIMULATION DESIGN OF DUAL ANGLE CNTROL CIRCUIT:

The simulation circuits and results illustrated in following figures validate the capability of the proposed DACin limiting the STATCOM negative sequence current when there is AC system fault at different locations of the 3-bus AC system.

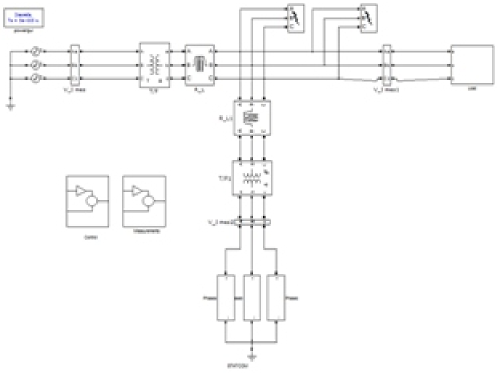

Fig.9.Matlab circuit of Dual Angle Controlled Statcom-connected to AC transmission system under faults.

In above circuit we are applying LG fault between phase A and ground during the interval 2 to 4 secondsand LL fault between phase A and phase A and phase B during the interval 4 to 6 seconds in the AC transmission system and the Statcom is working in capacitive mode and we observe the performance of Dual Angle Controlled Statcom to mitigate system faults.

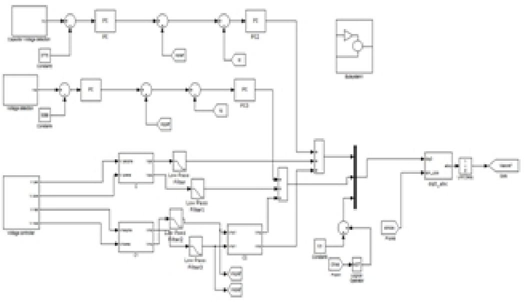

Fig. 10. Dual Angle Control circuit of STATCOM

From the above control circuit it is clear that we are comparing reference values of DC link capacitor voltage and source voltage with the actual values during fault conditions and controlling the voltages using voltage controller which uses the dual angle control technique and finally generating Vabc reference and giving it to the gating pulses of VSC in Statcom.

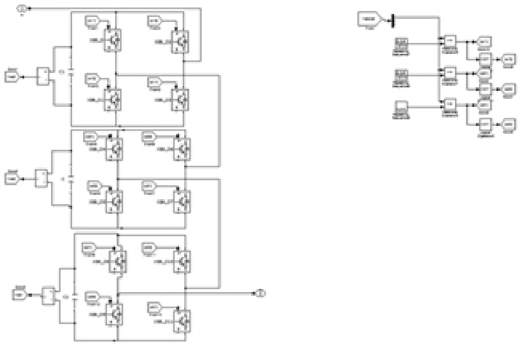

Fig.11. STATCOM internal circuit

VI. SIMULATION RESULTS:

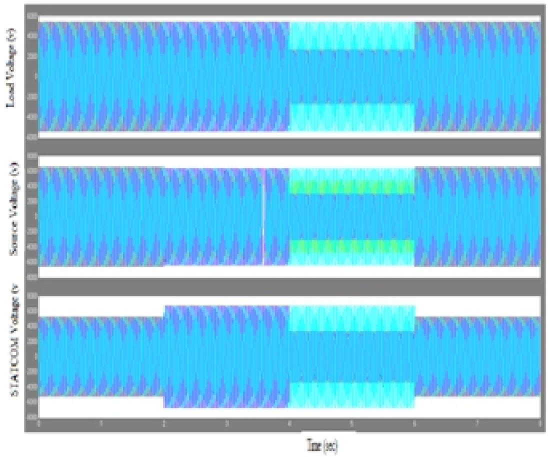

Fig.12.Load, Source and Statcom bus voltages when LG fault is applied between phase A and ground during the interval 2 to 4 seconds and LL fault between phase A and phase B during the interval 4 to 6 seconds.

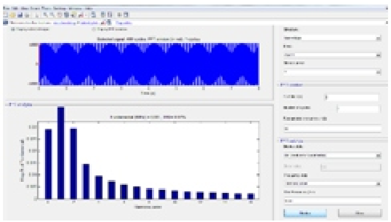

Fig.13.THD analysis of Load Voltage

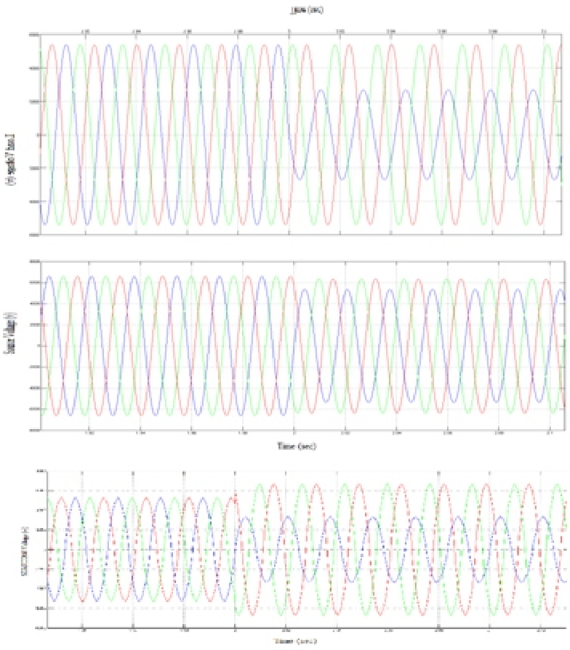

Fig.14. Load, source and Statcom voltage waveforms(zoom)

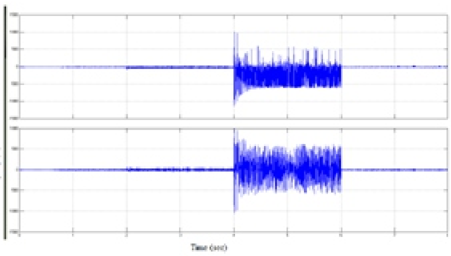

Fig.15. Negative sequence currents

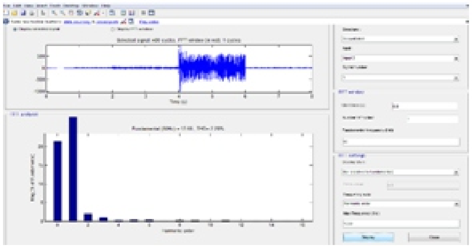

Fig.16. THD analysis of negative sequence currents

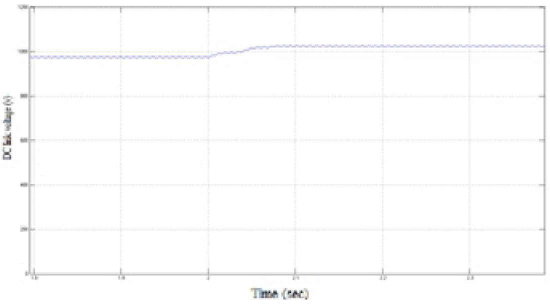

Fig.17. DC link voltage waveform

From the above results it is clear that Load voltage THD is reduced to 0.04% and also THD of negative sequence currents Id and Iq are reduced from 5% to 2.28% by using Dual Angle Controlled Statcom when compared to Angle Controlled Statcom and also DC link voltage 2nd harmonic oscillations are also reduced.The decreased DC-link voltage 2nd harmonic oscillations reduces the 3rd harmonic VSC output voltage and consequently the 3rd harmonic current of STATCOM tie line. Reduction in negative sequence current decreases the fault peak current.

VII.CONCLUSION :

In this paper, the performance ofangle-controlled STATCOM is improved under utility unbalanced conditions and system faults by using the proposed Dual Angle Controlled STATCOM.

The proposed structure is designed based on adding an appropriate oscillation (αac) to the conventional Angle-controller output(angleα).The angle αac is controlling the DClink voltage oscillations with twice the line frequency to generate the required negative sequence voltages at VSC output terminals to attenuate the effects of the postulated negative sequence bus voltage. This generated negative sequence voltage results in reduction of the negative sequence current seen by the STATCOM. Since this control structure is using two angles for controlling VSC output voltage, it is called Dual Angle Control (DAC) strategy. The main improvement is to significantly decrease the negative sequence current and DC-link voltage oscillations and Total Harmonic Distortion of output voltages under power system faults through control. Simulation results verified the validity of the proposed Dual Angle control structure.

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AUTHOR’S PROFILE:

G. Sriram Prasad is currently pursuing his M.Tech in Power Electronics from CMR College of Engineering & Technology affiliated to JNTUH University. He received his B.Tech degree from JNTUK University, in 2012, and his field of interest includes Power Electronic Control of Drives, FACTS.

Mr. G.Devadas is currently working as Professor, Electrical & Electronics Engineering in the Department of EEE, CMR College of Engineering & Technology, Kandlakoya, Hyderabad. He obtained his B.Tech degree in 1997 from NAGARJUNA UNIVERSITY and M.Tech degree in 2002 with a specialization in Power Systems and Automation from ANDHRA UNIVERSITY ,VISAKHAPATNAM, INDIA. He had 15 years of teaching experience. During his teaching career he taught various subjects like Electrical Machines, Power Systems and Control Systems, etc. His research interests include Power Quality, Wavelet Transforms, Neural & Fuzzy expert Systems.

K. Soujanyais currently working as Associate Professor, Electrical & Electronics Engineering in the Department of EEE, CMR College of Engineering & Technology, Kandlakoya, Hyderabad.She obtained her M.Tech degree from NIT Warangal with a specialization in Power Electronics and Drives. She obtained her B.Tech degree from Kakatiya University. Her areas of interest includes Power Electronics and Drives, FACTS.