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Enhancement of Voltage Regulation and Transient Stability of Six Phase STATCOM using Decoupled Current Control Strategy

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ABSTRACT- STATCOM is used in a six-phase transmission system to improve voltage regulation and transient stability. Six-phase pulse width modulated voltage source converters are used in the design of STATCOM, and a decoupled current control approach is used to operate it. The voltage references used by the voltage source converters' pulse generator are produced using a decoupled control method. This control technique allows for the decoupling of the coupling effect or the dependence of the d and q currents on one another, which improves system performance under unusual and abnormal conditions. By using the pulse generator of voltage source converters, the inner current control loop and the outer voltage control loop are intended to produce the necessary reference voltages. Simulation results are presented using MATLAB/SIMULINK to check efficacy of proposed six phase STATCOM.

General Terms: Six Phase transmission.
Keywords: STATCOM, Decoupled Control Strategy, Six Phase Transmission, Voltage Regulation, Transient Stability.

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1. INTRODUCTION

Due to increasing power demand, necessity for transmitting huge quantities of electrical power up to distribution point to feed the consumers is increasing. To reduce power losses, to increase transmission capability of transmission lines and to reach long distance consumer points, power is transmitted at increased voltage in the range of extra high and ultra-high levels. But in terms of insulation, protection of transmission line and other equipment, over voltages, corona losses and EMI inferences, it is becoming difficult to transmit power in such ultra-high levels of voltages [1–3]. In recent times, as exaltation and as a substitute, attention on power transmission using six phase to increase power transfer capability of transmission lines is increasing. Three phase system can be converted into six phase by using special transformer connection [4-6].

Six-phase transmission seems to be the utmost capable amid the multiphase systems. Numerous papers have been written and published on a variety of aspects of this new power transmission technology due to the increased interest in the subject, including viability dependability, fault investigation, safety schemes, and the conversion of some existing double-circuit 3-phase lines to 6-phase. In recent publications authors proposed 6-phase generators for high power applications [7-10]. The multiphase system, whenever apprehended, will constantly be unified into a 3-phase system. Three to six phase converting transformer with special connection will be required to connect multiphase systems to the rest of the network. While converting into six phase using converting transformer voltages are stepped up and then at distribution side or at receiving side these voltages are stepped down to three phase using six to three phase converting transformer. Y/double Star, Δ/double Star, Y/Hexagon, Δ/Hexagon etc. are the different types of connections required by transformers for converting three phase to six phase and vice versa. Clearly, to study a multi-phase systems, acceptable illustration of the transformers are of main importance.

Since 2000's efforts have been applied on research for economic viability of converting three phase double circuit lines to six phase lines. With fewer assemblies and a lower overall cost, six-phase transmission can transport the same amount of power as three-phase transmission. With same amount of electric field and same noise compared to double circuit three phase transmission, six phase transmission can deliver more power. Existing double circuit three phase transmission systems are compatible to six phase transmission as there is only requirement of transformer connection modification. The design of the equipment for the 4,5 phase is complicated and expensive. In case of six phase transmission it is difficult to transposition the transmission lines. Transient instability, poor voltage regulation and partial and insufficient

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availability of protection methods are the main drawbacks of six phase transmission. In this paper a six phase STATCOM (Static Compensator) is introduced in six phase transmission system to improve voltage regulation and to enhance transient stability after fault incidence.

On account of increased controlling of voltage and reactive power, static compensators (STATCOMs) constructed using six-phase pulse width modulated voltage source converters, have been proposed for voltage regulation and transient stability improvement in six phase transmission system. Most of the research on STATCOM control distillates on regulation of STATCOM output current and dc bus voltage for a reference reactive power. PI controllers are used for regulation of DC link voltage and reactive power references [11]. In this paper, the STACOM is modelled as controlled current source and error in voltage magnitude is used to generate reactive current and error in DC link voltage is used to generate active current.

This paper presents a six phase STATCOM using voltage source converters on six phase transmission system to improve voltage regulation and transient stability. Regularization of PCC voltage improves the overall performance of the system by improving the transient stability. The inner current control loop and the outer voltage control loop are designed for pulse generation required by STATCOM. Reference currents required by the STATCOM control system are generated from PI controllers to which error in DC link voltage and error in voltage magnitude are the inputs. Decoupled control strategy is adopted to generate voltage references required by pulse generator. Generation of reference signal by using a decoupled controlling will enhance transfer behavior of each output variable. Six-phase transmission system and its transformer connections are explained in *Section 2*. Six-phase STATCOM and its control strategy is explained in *Section 3*. Simulation results are presented in *Section 4*. Conclusion is given in *Section 5*.

2. SIX PHASE TRANSMISSION SYSTEM

Transmission of electrical energy using multiphase lines is considered as a workable alternative to existing systems in which it's possible to get effectual space consumption and rise in transmission skill to satisfy increasing consumer demand. Most promising among the multiphase systems is six-phase transmission due to its increased capability (1.732 times the existing three phase system) of transmission loading and requirement of minimum modification from existing three-phase systems. Three-phase to six phase transmission using Y/Star transformer is shown in *figure 1*.

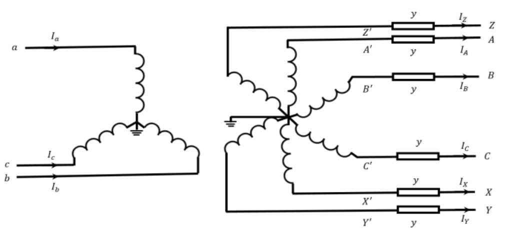

Figure 1: Transformer connection for six phase conversion

3. SIX PHASE STATCOM

STATCOM or static compensator connected to transmission line in parallel is a compensation device for reactive power and improves power quality. Other advantages of STATCOM are damping of the oscillations during abnormal conditions, stabilizing the line during transient, reducing voltage flicker, compensating sag and swell condition and controlling active and reactive power in the line. STATCOM comprises of a voltage source converter with power semiconductor switches which are controlled by a system which takes line voltages and currents as feedback [12-14].

By injecting or by absorbing the reactive current into the line in shunt, static compensator or STATCOM can achieve its assigned objectives. The STATCOM, not like a regular static VAR generator, has the capability to inject or absorb active power through the line by charging and discharging of the DC link capacitor.

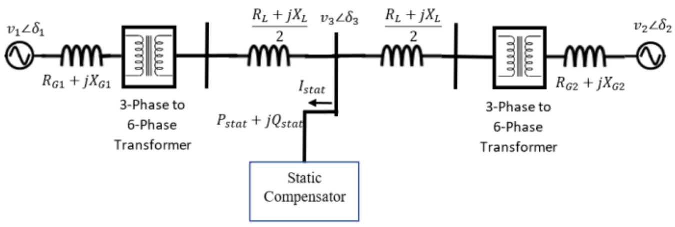

Figure 2: Six phase Transmission system with Static Compensator

But, if an additional energy storage system is accessible other than capacitor, the active power essentially controlled to a value which average per unit time period is equal to zero and can recompense for the power losses in the system. STATCOM add reactive power into the line required by load in the system by injecting reactive current having a variable magnitude and having phase angle in quadrature with line voltage. Capacitor connected at DC side of the STATCOM is required to maintain constant DC Voltage as required by the inverter to inject variable current into the line.

STATCOM converts constant DC voltage into multiphase voltage which are synchronized with PCC voltage and enhances dynamic stability of the PCC voltage. PCC voltage can be regulated by controlling amount of reactive power injected or absorbed into the power system by STATCOM. Reactive power is absorbed by shunt connected voltage source converter of STATCOM if the voltage in line is more than rated voltage, and if it is less reactive power can be generated and injected into the PCC for restoring the voltage.

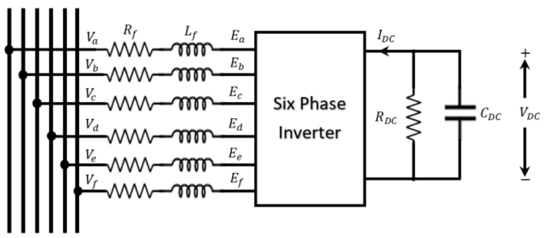

Figure 3: STATCOM connected at PCC

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At fundamental frequency, current and voltage equations of 6 phase STACOM can be defined as

$$\frac{d}{dt} i_{abcdef} = -\frac{R_s}{L_s} i_{abcdef} + \frac{1}{L_s}(E_{abcdef} - V_{abcdef}) \quad (1)$$

Losses due to internal resistance and inductance of STATCOM transformer such as copper losses and iron losses are represented using R_s and L_s. i_{abcdef} are line currents injected by STATCOM into the PCC. $E_{abcdef}$are converted voltages by six phase inverter of STATCOM, V_{abcdef} phase voltages at PCC.

E_a can be given as

$$E_a = mV_{dc}\cos(\omega t + \alpha) \quad (2)$$

V_{dc} is DC side voltage of STATCOM inverter, m is the modulation gain, α is injected voltage phase angle.
Phase voltage at PCC V_a can be represented as

$$V_a = \sqrt{2}V_s \cos(\omega_s t + \theta_s) \quad (3)$$

Equivalent equation of the STATCOM is converted into synchronous reference frame for dynamic model development and it is represented as

$$\frac{d}{dt}\begin{bmatrix} i'_{d1} \\ i'_{q1} \\ i'_{d2} \\ i'_{q2} \\ V'_{dc} \end{bmatrix} = K_s \begin{bmatrix} i'_{d1} \\ i'_{q1} \\ i'_{d2} \\ i'_{q2} \\ V'_{dc} \end{bmatrix} - \frac{\omega_s}{L'_s}\begin{bmatrix} V_s \cos\theta_s \\ V_s \sin\theta_s \\ V_s \cos(\theta_s + \beta) \\ V_s \sin(\theta_s + \beta) \\ 0 \end{bmatrix} \quad (4)$$

Active and reactive power injected by STATCOM into PCC is given as

$$P = V_s(i_{d1}\cos\theta_s + i_{q1}\sin\theta_s + i_{d2}\cos(\theta_s + \beta) + i_{q2}\sin(\theta_s + \beta)) \quad (5)$$

$$Q = V_s\left(i_{d1}\sin\theta_s - i_{q1}\cos\theta_s + i_{d2}\sin(\theta_s + \beta) - i_{q2}\cos(\theta_s + \beta)\right) \quad (6)$$

Reactive power support and regularization of DC link voltage are two objectives of STATCOM controlling system. By controlling the phase angle and by regulating switching pulses to STACOM these two objectives can be achieved. Due to the discrete topographical nature of the power system several power system restraints conditions are unattainable as controlling elements, hence state feedback control is placed occasionally in power system regularization. As local STATCOM states are available as feedback state feedback control is possible. For STATCOM voltage response control due to the almost linear behavior of the STATCOM response many controllers constructed on state feedback control.

Apart from providing voltage regulation, a STATCOM has the efficient ability to hold dynamic system changes, like stabilizing the system during transient conditions and reducing the power oscillations. In addition, with voltage regulation, the STATCOM can act as a reactive power source when there is a requirement to prevent quick and unpredicted voltage oscillations because of faults, sudden load changes, line outages, generator failures etc. The compensator should have sufficient VAR capacity to achieve these objectives to handle volatile dynamic instabilities. This can be achieved with an automatic control that keeps pre-arranged VAR reserve by altering the working point of the compensator.

By replacing capacitor with an energy storage device STATCOM can able to exchange active power with the power system it connected in addition with reactive power compensation. It can also regulate energy absorption from PCC to energize the storage device. This possible skill delivers a novel tool for improving active compensation, enhancing power system efficiency and, possibly, avoiding power outage.

Controlling procedure for 6 phase STATCOM is shown in *fig 4*. DC link voltage regulation across the capacitor of STATCOM at DC side and PCC voltage regulation by injecting or absorbing the reactive power into the line are main objectives of this controlling strategy. Six phase voltages and currents are converted into DQ frame by means of phase locked loop using following conversion.

Two outer loops and four inner loops are constructed to generate reference voltages required by six phase voltage source converters of STATCOM.

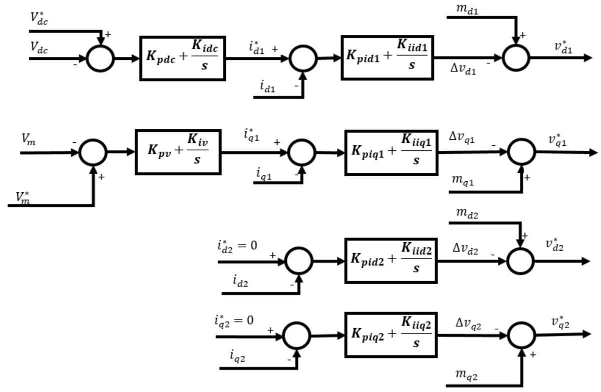


Figure 4: Control strategy for STATCOM

Two outer loops regulate the DC link voltage across the capacitor and AC voltage at PCC using PI controllers. Output of the PI controller of first outer loop is i_{d1}^* and it regulates active power flow of STATCOM from capacitor to PCC.

$$i_{d1}^* = K_{pdc}(V_{dc}^* - V_{dc}) + K_{idc}\int_0^t (V_{dc}^* - V_{dc})dt \quad (7)$$

Output of the PI controller of second outer loop is i_{q1}^* and it regulates reactive power flow of STATCOMto PCC and hence regulated PCC voltage.

$$i_{q1}^* = K_{pv}(V_m^* - V_m) + K_{iv}\int_0^t (V_m^* - V_m)dt \quad (8)$$

i_{d1}, i_{q1}, i_{d2} and i_{q2} are regulated to their respective reference values generated in outer loops by using four inner current loops using PI controllers. For better voltage regulation and reactive power compensationi_{d2}^* and i_{q2}^* are considered to be zero.

V_m is given as

$$V_m = \frac{1}{\sqrt{3}}(V_a^2 + V_b^2 + V_c^2 + V_d^2 + V_e^2 + V_f^2) \quad (9)$$

While generating reference voltages required by 6 phase VSC of STATCOM, decoupled current control is adopted. As a multivariable system, in which input and output are coupled, a change in one variable will affect several other variables. Generation of reference signal by using a decoupled controlling will enhance transfer behavior of each output variable. A detailed description of crosswise decoupling control by means of stationary state feedback was first developed in [15-18]. Reference voltages in DQ frame are generated as

$$v_{d1}^* = \Delta v_{d1}^* + m_{d1} \quad (10)$$

Where decoupled feed forward term $m_{d1}$is given as

$$m_{d1} = v_{d1} + I_{d1}R_f - I_{q1}\omega L_f \quad (11)$$

$$v_{q1}^* = \Delta v_{q1}^* + m_{q1} \quad (12)$$

Where m_{q1} is given as

$$m_{q1} = v_{q1} + I_{q1}R_f + I_d\omega L_f \quad (13)$$

$$v_{d2}^* = \Delta v_{d2}^* + m_{d2} \quad (14)$$

Where decoupled feed forward term m_{d2} is given as

$$m_{d2} = v_{d2} + I_{d2}R_f - I_{q2}\omega L_f \quad (15)$$

$$v_{q2}^* = \Delta v_{q2}^* + m_{q2} \quad (16)$$

Where m_{q2} is given as

$$m_{q2} = v_{q2} + I_{q2}R_f + I_{d2}\omega L_f \quad (17)$$

Δv_{d1}^* , Δv_{d2}^* , Δv_{q1}^* and Δv_{q2}^* are required change in VSC converter reference voltages to reduce error between actual STATCOM currents (i_{d1}, i_{q1}, i_{d2} and i_{q2}) and refence currents (i_{d1}^*, i_{q1}^*, i_{d2}^* and i_{q2}^*) which are regulated by PI controllers.

$$\Delta v_{d1}^* = K_{pid1}(i_{d1}^* - i_{d1}) + K_{iid1}\int_0^t (i_{d1}^* - i_{d1})dt \quad (18)$$

$$\Delta v_{q1}^* = K_{qid1}(i_{q1}^* - i_{q1}) + K_{iiq1}\int_0^t (i_{q1}^* - i_{q1})dt \quad (19)$$

$$\Delta v_{d2}^* = K_{pid2}(i_{d2}^* - i_{d2}) + K_{iid2}\int_0^t (i_{d2}^* - i_{d2})dt \quad (20)$$

$$\Delta v_{q2}^* = K_{qid2}(i_{q2}^* - i_{q2}) + K_{iiq2}\int_0^t (i_{q2}^* - i_{q2})dt \quad (21)$$

STATCOM's reactive power output can be limited to the reference value which is given as the input the control system by PI controller [19-20]. The PI Controller gain is tuned by using Control system Tuner. To oppose transient instabilities, compensator deviates its output rapidly by using well-tuned controllers. With constant reactive power output, during fluctuations in the system a new voltage reference point can be set to back the reactive power support and to achieve the steady state point. To improve transient stability of the power system, compensator injects leading capacitive current at low PCC voltage.

4. SIMULATION RESULTS

To check the effectiveness of the proposed control system for six phase STATCOM on transmission system shown in *figure 2*, for voltage regulation, reactive power compensation and for power oscillations damping, simulations are carried out using MATLAB/SIMULINK. Parameters of STATCOM and power system are given as under and PI controller gains of control system depicted in *figure 4* are tuned using trial and error method by taking certain system conditions. The two-zone power system consists of 138KV, 50Hz 100KM six phase transmission line and fed by 200MVA 13.8KV 50Hz three phase source at sending and receiving ends. The generators at sending and receiving ends are assumed to be ideal voltage sources behind equivalent Thevenin's impedance. The transmission lines of power system are modelled as distributed-parameter line. Transformer configuration of Y/double Y shown in *figure 1* is adapted to transform three phase system into six phase system. A 200MW, 75MVAR load is connected at receiving end side of the transmission system. Sinusoidal pulse width modulation with fixed switching frequency has been used to control 6 phase converter voltage. Reference values of V_{d1}^*, V_{q1}^*, V_{d2}^* and V_{q2}^* are calculated from decoupled controlling and transformed into V_a^*, V_b^*, V_c^*, V_d^*, V_e^* and V_f^*.

SPWM receives the reference values as input and generate the pulses required by 6 phase voltage source converter. The DC link voltage across the capacitor can be converted 6 phase voltages and injects shunt current into PCC to improve voltage regulation of power system.

***Case 1*: Voltage regulation**

Efficacy of proposed six phase STATCOM with decoupled control strategy is examined by changing V_m^*. Capability of voltage magnitude at PCC to track reference value depends on well-tuned PI controller gains. Trial and error method is adopted to find K_p and K_i gains of PI controller. V_m^* is 1 p.u initially then reduced to 0.95 p.u at 0.1 seconds and increased to 1.05 p.uat 0.3 seconds then returned 1 p.u a 0.5 seconds. Variation of reference value and actual value of voltage magnitude at PCC is shown in *figure 5*. Actual voltage is tracking the reference value with a peak overshoot of 0.46%and steady state error of 0.03%. Instantaneous voltages at PCC during voltage regulation is shown in *figure 6*. Six phase voltages during change in reference value from 1 p.u. to 0.95 p.u. is shown in *figure 6a* and during change in reference values from 0.95 p.u. to 1.05 p.u. is shown in *figure 6b*. Direct axis and quadrature axis currents of STATCOM (I_{d1} and I_{q1}) are shown in *figure 7*.

Increase in voltage magnitude requires reactive power support at PCC by STATCOM and hence I_{q1} is increasing positively at 0.1 seconds and negatively at 0.3 seconds. Change in active power flow through STATCOM due is voltage reference change is represented by I_{d1}. DC link voltage across the capacitor is regulated to reference DC voltage which is due to change in I_{d1}as shown in *figure 8*.

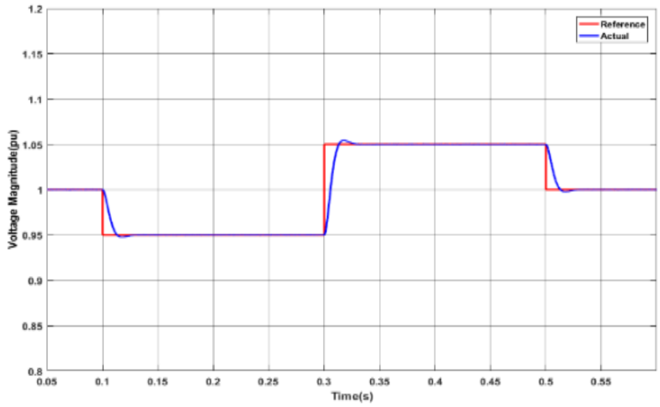
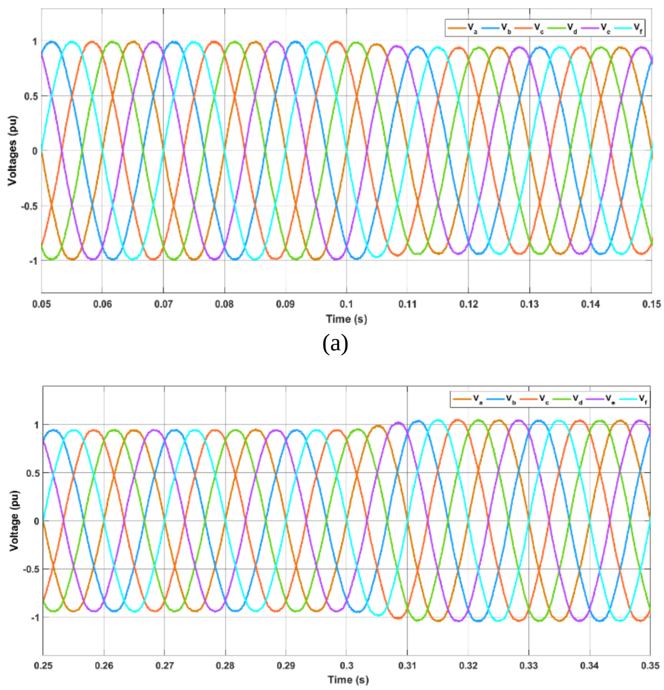


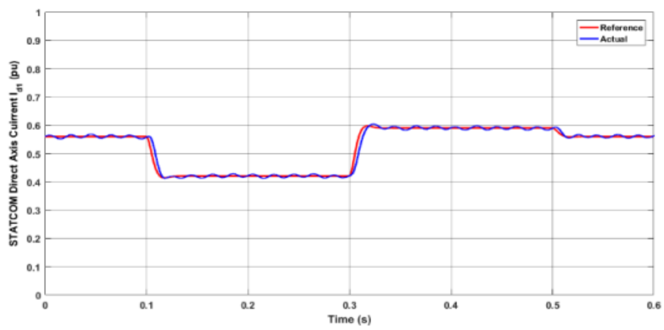
Figure 5: Voltage Magnitude at PCC during change in voltage reference



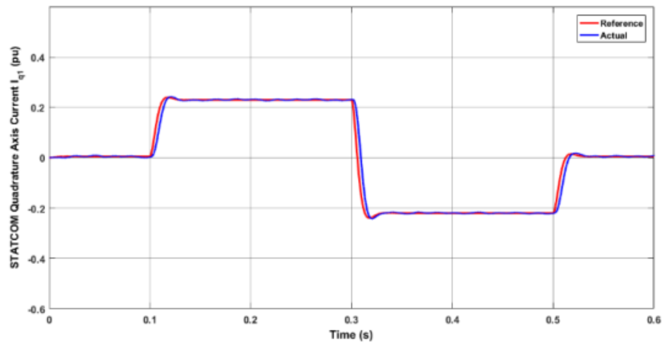
(a)

(b)

Figure 6: Six phase instantaneous voltages during change in voltage reference (a) 1 pu to 0.95 pu (b) 0.95 pu to 1.05 pu



(a)



(b)

Figure 7: Direct and Quadrature axis currents ($\mathbf{I_{d1}}$ and $\mathbf{I_{q1}}$) during change in voltage reference (a) $\mathbf{I_{d1}}$ (b) $\mathbf{I_{q1}}$

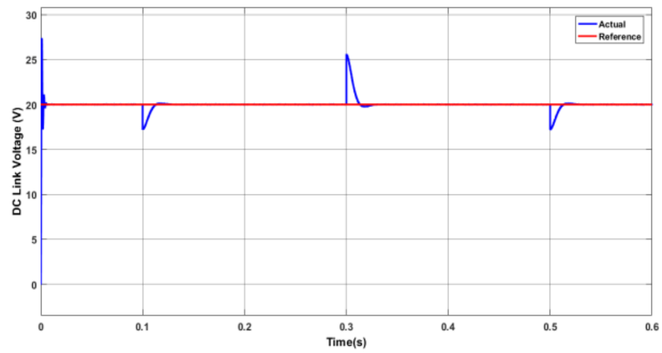


Figure 8: DC Capacitor link Voltage during change in voltage reference

Case 2: Six phase to ground fault

To investigate the transient behavior of STATCOM, a six phase to ground fault is applied at PCC at 0.25seconds and fault is removed after 0.15 seconds. due to very low resistance path between six phase and ground voltage dropped to zero at PCC after fault then the voltages are recovered after removal of fault. Recovery time for voltages to reach steady state is 0.11 seconds and peak value reached after removal fault is 1.7 p.u. Without STATCOM voltage recovery time is 0.8 seconds and peak value reached is 2 pu. Voltage magnitude during fault removal at PCC without STACOM is shown in *figure 9*. Voltage magnitude during fault at PCC with STATCOM is shown in *figure 10*. Instantaneous six phase voltages during fault is shown in *figure 11*.I_{d1}, I_{q1} and DC link voltage V_{dc} are shown in *figure 12 and 13*.

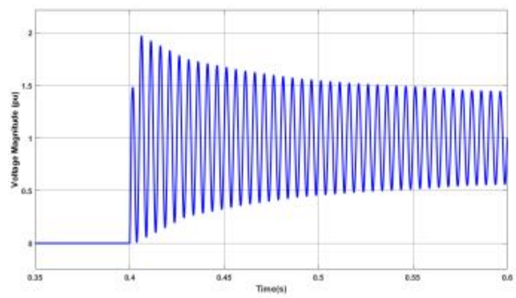


Figure 9: Voltage Magnitude at PCC after fault without STATCOM

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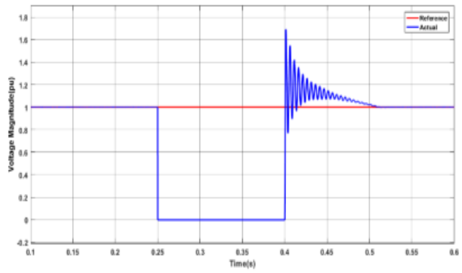


Figure 10: Voltage Magnitude at PCC during Fault

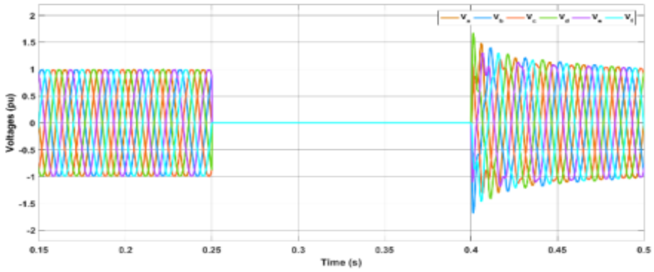
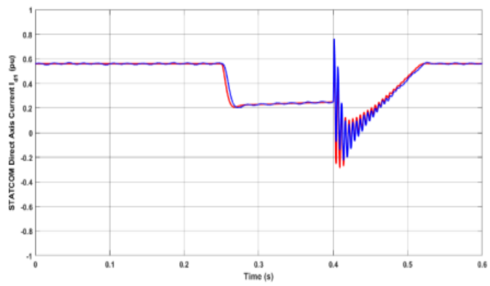
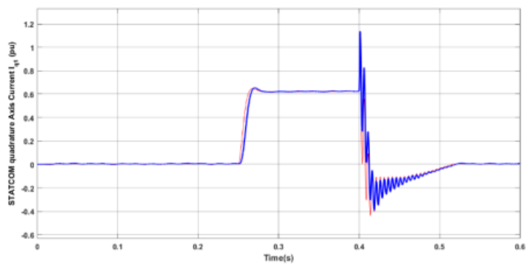


Figure 11: Six phase instantaneous voltages during Fault



(a)



(b)

Figure 12: Direct and quadrature axis currents ($\mathbf{I_{d1}}$ and $\mathbf{I_{q1}}$) during Fault (a) $\mathbf{I_{d1}}$ (b) $\mathbf{I_{q1}}$

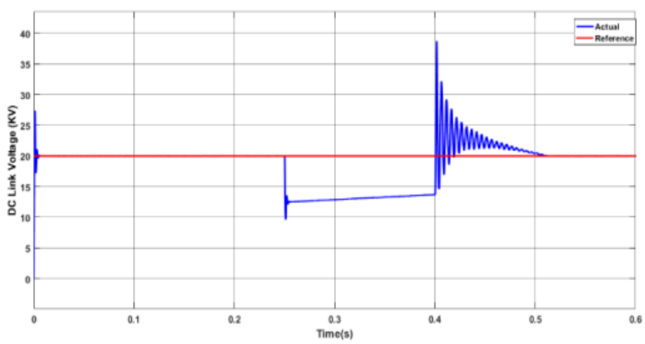


Figure 13: DC Capacitor link Voltage during Fault

***Case 3*: Voltage Sag**

Voltage sag of 20% is applied at sending end side 6 phase transmission line to check feasibility of STATCOM to control voltage regulation at PCC. Due to increase in injected reactive current I_{q_1} at PCC, voltage is recovered and maintained almost 1 p.u during sag. Instantaneous voltages at sending end and PCC are shown in *figure 14*. Reference and actual values of voltage magnitudes are shown in *figure 15*. Reactive current increase to maintain constant voltage PCC is shown in *figure 16*. Regulated DC link voltage is shown in *figure 17*.

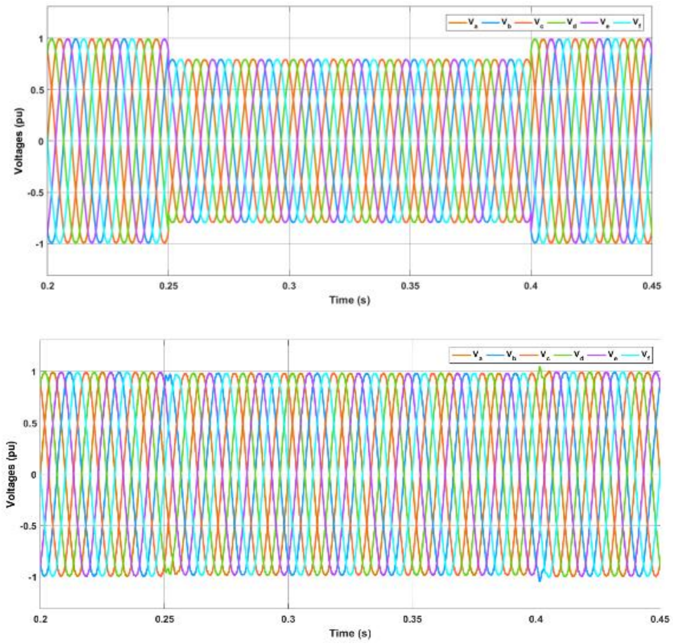


Figure 14: Sending End and PCC voltages during Sag

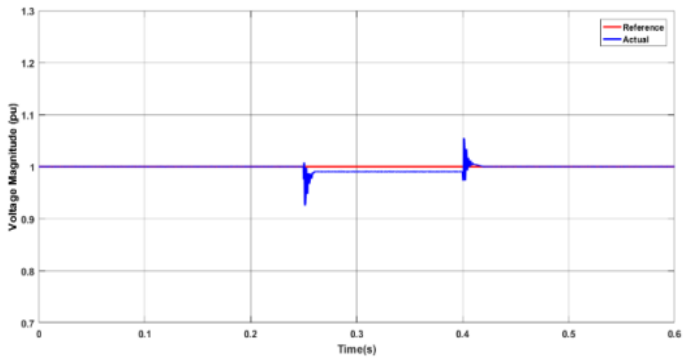
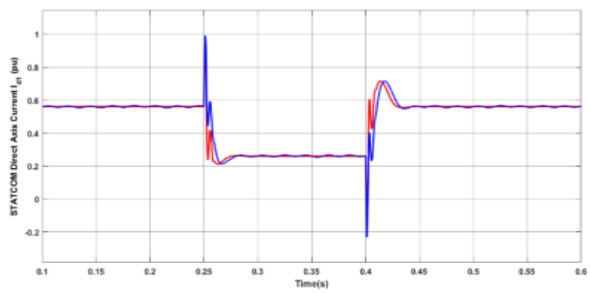


Figure 15: Voltage Magnitude during sag



(a)

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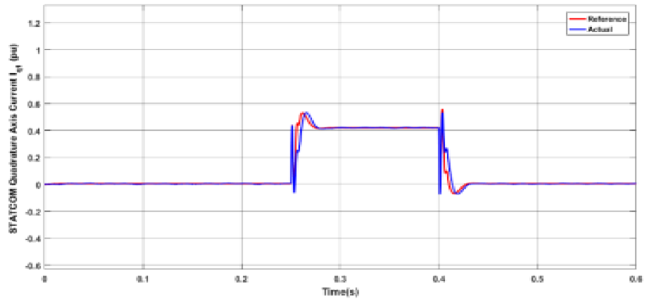

(b)

Figure 16: direct and quadrature axis currents ($\mathbf{I_{d1}}$ and $\mathbf{I_{q1}}$) during Sag (a) $\mathbf{I_{d1}}$ (b) $\mathbf{I_{q1}}$

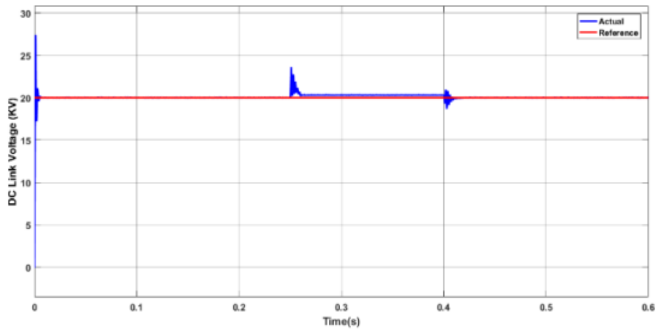

Figure 17: DC Capacitor link Voltage during Sag

***Case 4*: Voltage Swell**

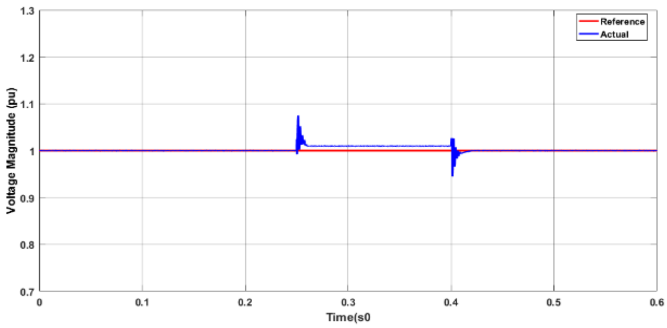

Figure 18: Voltage Magnitude at PCC during Swell

In this case voltage swell of 20% is applied at sending end side of 6 phase transmission line. Due to increase in injected reactive current I_{q_1} in negative at PCC, voltage is recovered and maintained almost 1 p.u during swell. Instantaneous voltages at sending end and PCC are shown in *figure 18*.

5. CONCLUSION

A control strategy for a STATCOM in a six-phase transmission system for voltage regulation improvement and for transient stability improvement is designed in this paper. The proposed decoupled control strategy reacts well to the network instabilities by preserving the steady state voltage level. This is made possible by better reference current tracking, which enhances the support for reactive power during transient periods. The reactive power injection and absorption between the STATCOM and six phase transmission system is controlled and voltage magnitude at PCC is regulated by four well-tuned PI controllers. Decoupled control strategy is used to generate reference signals to enhance transfer behavior of each output variable. Simulation results using MATLAB/SIMULNK are presented to check efficacy of proposed STATCOM.

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