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STATCOM-Based 48-Pulses Three Level GTO Dedicated to Voltage regulation and Reactive Power Compensation

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ABSTRACT: Constrained by the political, economic and in particular environmental restrictions, Today's electrical power systems are being operating under the ever increasing utilization of the exciting transmission lines. Consequently, power systems are continuously facing severe quality problems such as overloaded lines, high reactive power, buses voltage violation and harmonics current burden. The Static Synchronous Compensator (STATCOM), with the option that controls the voltage profile by means of reactive power, could be very effective in controlling the characteristic of the power system during higher loading and contingencies outages. This paper deals an improvement of power quality and voltage regulation using an advanced STATCOM. The technology of this STATCOM is based on a 48-pulse GTO voltage source converter (VSC). The proposed concept enables the regulation of the power voltage profile and the compensation of the reactive power by absorbing or generating a flow of current equivalent to the required reactive power. Furthermore, it enables the cancellation of the current harmonics. The performance of the proposed concept is simulated in the MATLAB environment considering an overloaded and short-circuited real-life case study.

KEYWORDS: STATCOM, reactive power compensation, decoupled control strategy, power quality, voltage regulation.

I.INTRODUCTION

Constrained by the limitation of energy resources and the political, economic and in particular environmental restrictions, worldwide transmission systems are forced to operate under the ever increasing utilization and the higher loading of the exciting transmission lines. Besides, most of the loads are nonlinear or unbalanced. Consequently, power systems are continuously facing severe quality problems such as overloaded lines, harmonics current burden, poor voltage regulation, high reactive power, etc. The reliable and secure operation of power system is highly depending on reducing and controlling these problems. In fact, if not controlled properly, they may lead to a total or partial system contingency outage. Approaches and techniques enabling the eradication of such power quality problems have been discussed in many articles so far in an attempt to achieve a more secure and high quality power production. A review of Literature reveals that initial studies on the power quality improvement used passive filters. [1], others developed works using the active power filters. These devices provide compensation for reactive power, neutral currents and harmonics [2]. The revolution in technology of effect transistor (MOSFAT), metal-oxide semiconductor field and insulated gate bipolar transistor (IGBT) have led to the development of hybrid filters that provides better power quality in terms of effectiveness and cost [3]. Although some success of the above technologies in power quality improvement is achieved, several disadvantages such as: Excessive harmonics currents flow in the filters, parallel and series resonances, filters overloading are still subsisted. Recently, the power quality improvement is due to the effective of FACTS controller. FACTS have been used to protect sensitive loads from voltage sag, damping oscillations [4–8]. Application of FACTS in case of wind energy system connected grid is reported in [9–11]. The enhancement of voltage regulation in the distribution feeder is insured by installing a shunt compensator [12-13]. In [14], El-Moursi and Sharaf proposed a STATCOM based on a phase-shifting transformer (PST) and a three-leg VSC for power quality. In [15], a novel reactive power controller for the STATCOM has been proposed and its performance has been investigated. The

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previous works have demonstrated that the STATCOM is an interested key FACTS device. It is able to control the amount of reactive power exchanged the power system by means of a VSC that uses forced-commutated power electronic devices. Concerning the three-pulse GTO-VSCs, it has been reported in the literature that they suffer from a low power quality especially under several disturbances. Recently, their substitution by forty height-pulse ones has been the subject of intensive investigations. The forty height-pulse GTO-VSCs are proved to be effective in cancelling the impactct of poor load power factor, voltage regulation, neutral current compensation and harmonic elimination. The actual work proposes the control model of a 48-pulse GTO VSC and its integration in which one of a given grid in order to simulate its dynamic behaviour.

II. STATCOM

The STATCOM is a shunt connected device that regulates bus voltage magnitude *Vs* at the point where it is connected by exchanging reactive power with the AC system with various solid-state switching techniques. Although the basic architecture and working principle of the STATCOM have been widely explained in the literature [16-17], the revolution in technology of power electronics gives rise to a new GTO-VSC based STATCOM aspect. Its main building block is shown in Fig. 1 [18]. It comprises a 48-pulse VSC cascade model connected to the power system through a coupling transformer; a DC link working as an energy storage device and charged from the AC system, a measurement block needed for digital dynamic simulation, a decoupled current control system that insures dynamic regulation of *Vs* and a phase angle (α) controller for generating gate signals. A commanded three-phase 48 pulse AC output voltage waveform V_{STAT} is obtained by means of phase angle control (α) at the point of connection. The gap between *Vs* and V_{STAT} induce reactive power exchange between the power system and the STATCOM. Thereby, the STATCOM can be alternatively represented by a commanded voltage source V_{STAT} that is kept in quadrature to the STATCOM current I_{STAT}. The STATCOM working can be illustrated in figure 2 and can be detailed as follows [19]: When V_{STAT} is lower than V_s, the current flows from the AC system to the STATCOM. In this respect, the STATCOM device behaves as an inductance absorbing reactive power from the system bus. In the opposite case, the current flows from the STATCOM to the AC system and the FACTS device behaves as a capacitor generating reactive power to the system bus. However, when V_{STAT} is equal to V_s, there is no reactive power exchange between the two parts. This exchanged reactive power can then be worked out by regulating the magnitude of V_{STAT} with respect to V_s.

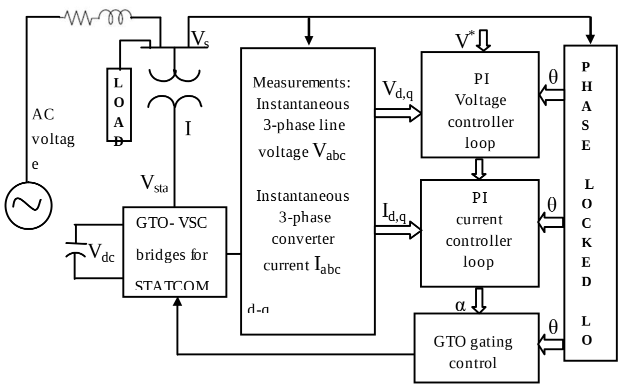

Fig. 1 GTO-VSC based STATCOM architecture

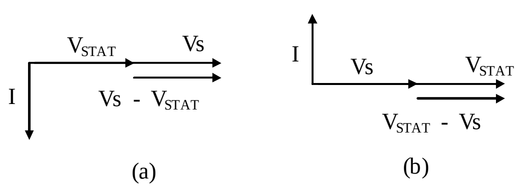

Fig. 2 STATCOM main operation: (a) inductive operation, (b) capacitive operation

III. THE 48-PULSE VOLTAGE SOURCE GTO CONVERTTER

Fig. 3 represent the circuit schema of the suggested 48-pulse STATCOM design. The 48-pulse model is carried out by four 12-pulse GTO-converters phase-shifted by 7.5° from each other and connected in parallel on the DC part with a DC capacitor (2000μF). The outputs from each pole of the four VSC are fed to secondary winding of four zig-zag phase shifting transformers connected in (Y) or (Δ), the primaries winding of the transformers are linked in series on

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the line part to electromagnetically add the outputs from the four 12-pulse GTO-converters. Thus, a composite multi-pulse voltage waveform of 48-steps with a displacement angle of 7.5° is achieved at the connection point [20].
In a multi-pulse operation, the harmonic content is decreased by using various pulses in each half sequence of the output voltage.
The phase-shift model on each 12-pulse converter is the next [21-23]:

$$v_{ab12}(t)_1 = 2[V_{ab1}\sin(\omega t + 30°) + V_{ab11}\sin(11\omega t + 195°) + V_{ab13}\sin(13\omega t + 255°) + V_{ab23}\sin(23\omega t + 60°) + V_{ab25}\sin(25\omega t + 120°) + ...] \quad (1)$$

$$v_{ab12}(t)_2 = 2[V_{ab1}\sin(\omega t + 30°) + V_{ab11}\sin(11\omega t + 15°) + V_{ab13}\sin(13\omega t + 75°) + V_{ab23}\sin(23\omega t + 60°) + V_{ab25}\sin(25\omega t + 120°) + ...] \quad (2)$$

$$v_{ab12}(t)_3 = 2[V_{ab1}\sin(\omega t + 30°) + V_{ab11}\sin(11\omega t + 285°) + V_{ab13}\sin(13\omega t + 345°) + V_{ab23}\sin(23\omega t + 240°) + V_{ab25}\sin(25\omega t + 300°) + ...] \quad (3)$$

$$v_{ab12}(t)_4 = 2[V_{ab1}\sin(\omega t + 30°) + V_{ab11}\sin(11\omega t + 105°) + V_{ab13}\sin(13\omega t + 165°) + V_{ab23}\sin(23\omega t + 240°) + V_{ab25}\sin(25\omega t + 300°) + ...] \quad (4)$$

The four 12-pulse AC output voltages given by eq. (1-4) are added by connecting in series the transformers secondary windings.

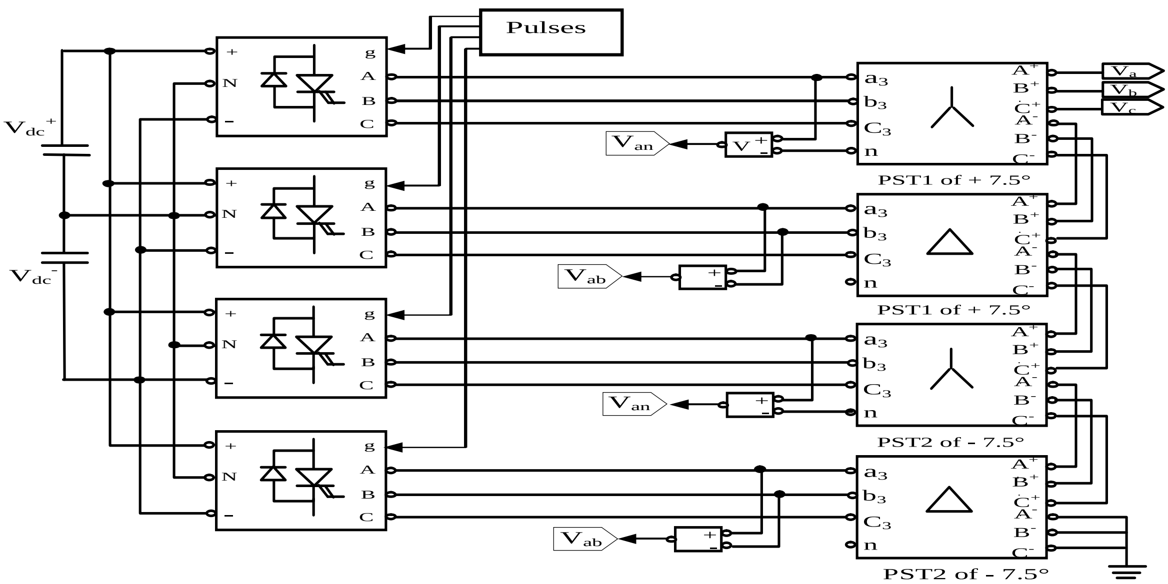

Fig. 3 Circuit layout of the proposed 48-pulse STATCOM configuration

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The output voltage of the 48-pulse is presented as follow:

$$v_{ab48}(t) = v_{ab12}(t)_1 + v_{ab12}(t)_2 + v_{ab12}(t)_3 + v_{ab12}(t)_4 \quad (5)$$

That gives:

$$\begin{aligned} v_{ab48}(t) = 8[&V_{ab1}\sin(\omega t + 30°) + V_{ab47}\sin(47\omega t + 150°) + \\ &V_{ab49}\sin(49\omega t + 210°) + V_{ab95}\sin(95\omega t + 330°) + \\ &V_{ab97}\sin(97\omega t + 30°) + ...] \end{aligned} \quad (6)$$

The line to neutral 48-pulse AC output voltage from the STATCOM model is expressed by:

$$v_{an48}(t) = \frac{8}{\sqrt{3}} \sum_{n=1}^{\infty} V_{abn} \sin(n\omega t + 18.75°n - 18.75°i)$$

$$\forall n = 48r \pm 1, r = 0,1,2.... \quad (7)$$

$i = 1$ for positive sequence harmonics and $i = -1$ for negative sequence harmonics.

Voltages $V_{bn48}(t)$ and $V_{cn48}(t)$ manifest an identical pattern shape from phase a unless a phase shifting of 120° and 240° respectively. Fig. 4 describes the resultant 48-pulse line-to-line (L-L) output voltage $V_{ab48}(t)$.

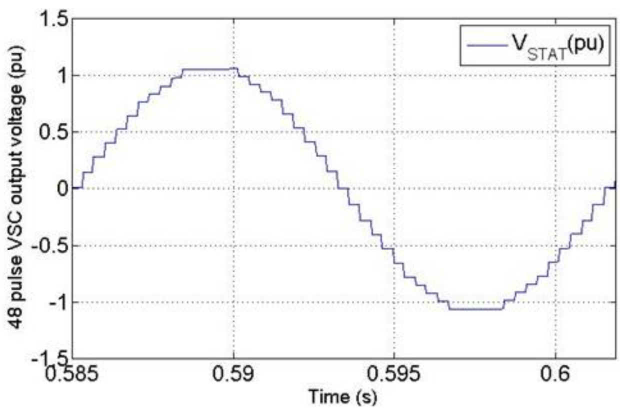

Fig. 4 48-pulse GTO-Converter output voltage

IV.PROPOSED CONTROL STRATEGY

Fig. 5 shows the decoupled control algorithm used for the STATCOM. This algorithm uses both direct and quadrature current components of the STATCOM AC current [24-25]. A set of instantaneous values of AC line voltages (V_{abc}) and converter current (I_{abc}) are measured in time domain and transformed in d-q components. A phase locked loop (PLL) uses the three phase line voltages at bus 2 to calculate the reference angle θ. This angle is needed to measure the direct axis and quadrature axis component of the AC three phase voltages V_{dq} and currents I_{dq}.
The magnitude of the line voltage (Vdq) is compared to the reference voltage V* and the error signal is controlled through an outer PI voltage loop (with $k_p = 36$ and $k_i = 9000$) to obtain the reference reactive current (I_q^*). The reference value I_q^* is then compared with the current quadrature component I_q, the resulting error is passed through a proportional plus integral PI controller with ($k_p = 5$ and $k_i = 40$) to produce a relative angle α of the GTO voltage with

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respect to line voltage of bus 2. The DC link capacitor is dynamically adjusted in relationship with the converter voltage.

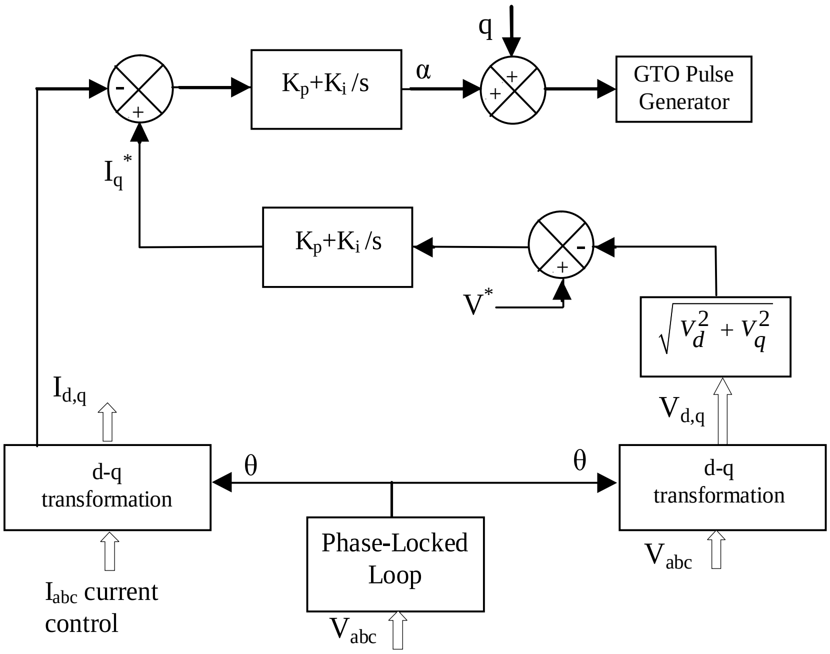

Fig. 5 STATCOM control schema

V. SIMULATION RESULTS AND DISCUSSION

The sample study radial power system is shown in Fig. 6. It consists of two 500-kV power grid equivalents (respectively 3000 MVA and 2500 MVA) connected by two 300-km transmission lines. A ±100Mvar STATCOM device is connected to the 500 kV (L–L) grid at bus 2. The full system parameters are given in the appendix.

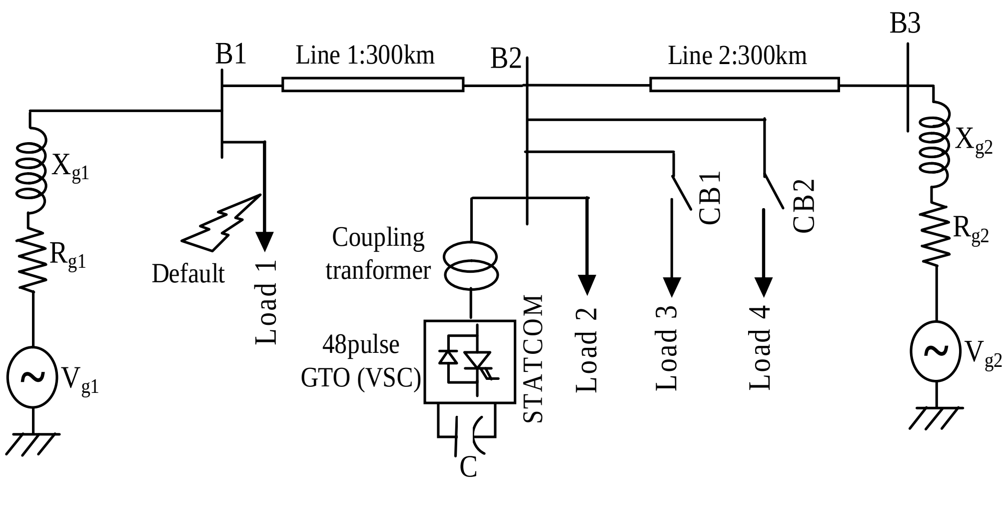

Fig. 6 The studied power system

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The simulation is performed by using the MATLAB/Simulink and power system blockset. The studied power system is subject to load switching at bus B2. Two main cases are discussed and compared in order to show performance of the STATCOM: Power system grid with and without STATCOM. For the two cases, the following excursion sequence detailed in Fig.7 is tested: First at $t = 0.1$ *Sec*, the network system feeds only load 1 and load 2. The measured voltage at bus 2 V_{SB2} as shown in Fig.8 is 1.029 pu for the uncompensated case and is equal to 1.02 pu for the compensated case. The STATCOM acts in inductive mode as shown in the first zoom of Fig. 7: $V_{SB2} > V_{STAT}$ and V_{SB2} lags the STATCOM current I_{STAT} by 90°. Therefore, it absorbs about 0.25 pu of reactive current from the AC power system as shown in Fig. 10. The STATCOM doesn't absorb active current to the network as shown in Fig. 11.
Plots of STATCOM exchanged active and reactive power with the AC network system are shown in Fig. 12 and Fig. 13 respectively. The STATCOM absorbs about 0.18 pu of reactive power from the AC network at bus 2 and extracts about 0.07 pu of real power to subsutitute the added losses. The exchanged reactive power between the shunt device and the AC network system acts by decreasing the transmitted real and reactive power to bus 2 as shown respectively in Fig. 14 and Fig. 15. The transmitted real power decreases from 13.15 to 13,08pu due to reactive power compensation. The transmitted reactive power also decreases from –0.25pu to -0.05pu. Next at $t = 0.5$ *Sec*, the load 3 is added to the AC network system at bus B2 by turning on the circuit breaker CB1, this leads, as shown in Fig. 8 to a decrease in bus 2 voltage to 1 pu for the uncompensated case. For the compensated case, the regulated voltage is kept equal to 1.02 pu. The DC capacitor voltage increases as shown in Fig. 9. The STATCOM is currently operating in the capacitive mode as shown in the second zoom of Fig. 7: $V_{SB2} < V_{STAT}$ and V_{SB2} leads the STATCOM current I_{STAT} by 90°. Therefore, it injects about 0.4 pu of reactive current to the AC network system. The shunt device current is fully a reactive current as shown in Fig. 10 and Fig. 11.

Plots of STATCOM exchanged real and reactive power with the AC network system are shown in Fig. 12 and Fig. 13 respectively. The STATCOM absorbs about 0.4 pu of reactive power from the AC network at bus 2. The exchanged reactive power between the shunt device and the AC network system acts by increasing the transmitted real and reactive power to bus 2 as shown respectively in Fig. 14 and Fig. 15. The transmitted real power increases from 12.24pu to 12,42pu oving to reactive power compensation. The transmitted reactive power also increases from -0.87pu to -0.7pu. Then at $t = 1$ *Sec*, the load 4 is now added to the power system at bus 2 by turning on the circuit breaker case, the regulated voltage is kept equal to 1.02pu. The STATCOM is still operating in the capacitive mode and acts by injecting about 0.75 pu of reactive current to the AC network system.
Plots of STATCOM exchanged real and reactive power with the AC network system shown in Fig. 12 and Fig. 13 respectively substantiate that the STATCOM injects more reactive power to the AC network at bus 2 (about 0.8 pu). This leads to more increase in the transmitted real and reactive power to bus 2 as shown in Fig. 14 and Fig. 15 respectively. The transmitted real power increases from 11.7 to 12 pu owing to reactive power compensation. The transmitted reactive power also increases from -1.35pu to -1.0pu. After that at $t = 1.5$ *Sec***,** both loads 3 and 4 are removed from bus B2. The power system network returns to its first situation. The shunt device operates in inductive mode to equalize the resultant overvoltage at bus B2 and the dc voltage decreases as indicated in Fig. 9. Finally, at $t = 2$ *sec*, a three phase short-circuit fault is applied at bus 1. Through analysing all plots during this disturbance period, one can notice a big oscillation during transient period followed by a steady state. Comparing the two cases, it’s sure that when the shunt device is installed, it successfully defers voltage from collapsing and therefore active and reactive power. This is due to the fact that it is able to provide or absorb immediate reactive power.
In all steps, it can be viewed that plots of transmission line real and reactive currents in Fig. 16 and Fig. 17 respectively are the same for both the compensated and uncompensated case. But it can be noticed that any increasing or decreasing of network loading will give rise to transmission line current changing. This can be clarified by the fact that the STATCOM regulates only bus voltage that induces change in transmission line current.

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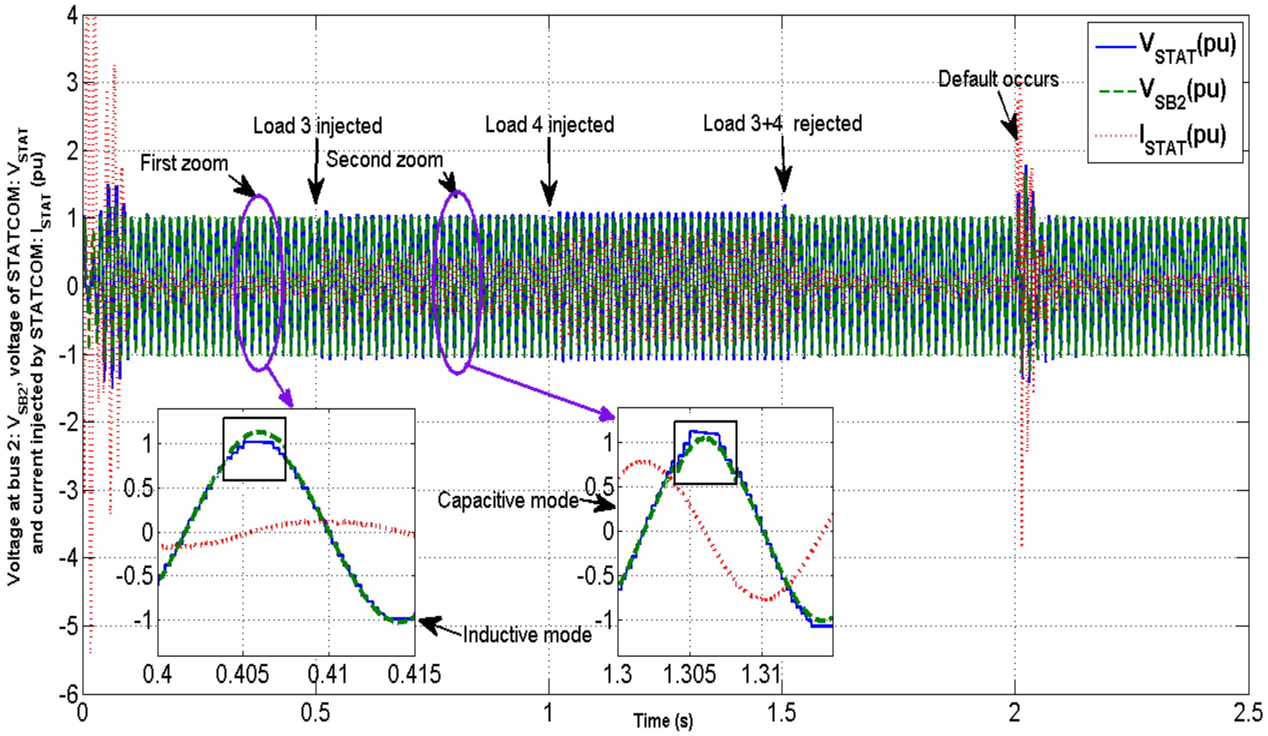

Fig. 7 Voltage of bus 2, STATCOM voltage and STATCOM in pu

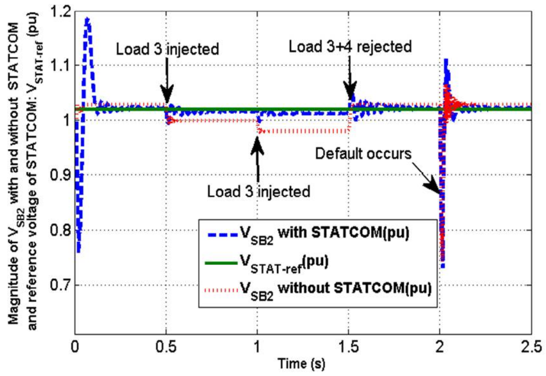

Fig. 8 V_{ref} and V_{SB2} with and without STATCOM in pu

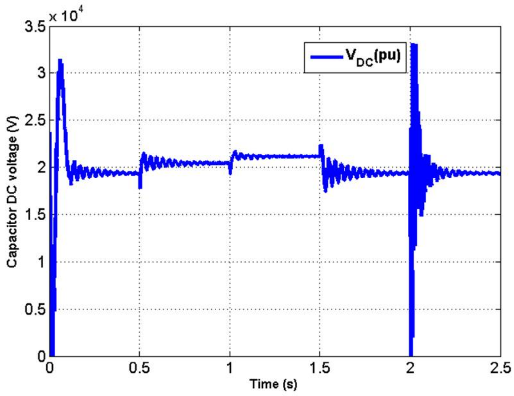

Fig. 9 Capacitor dc voltage in kv

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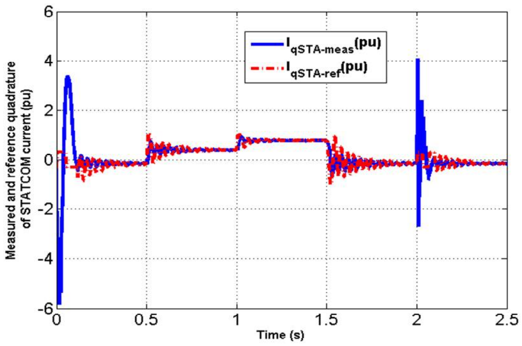

Fig. 10 Measured and reference of STATCOM current in pu

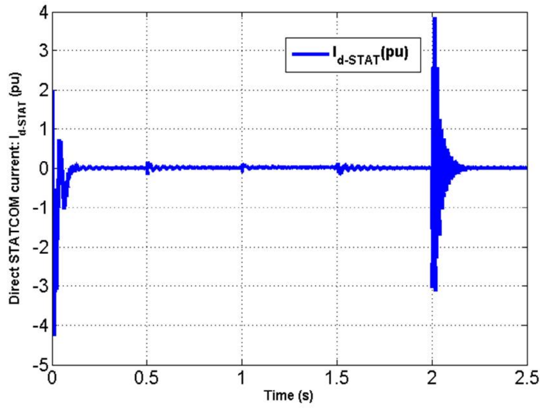

Fig. 11 Direct component of STATCOM current in pu

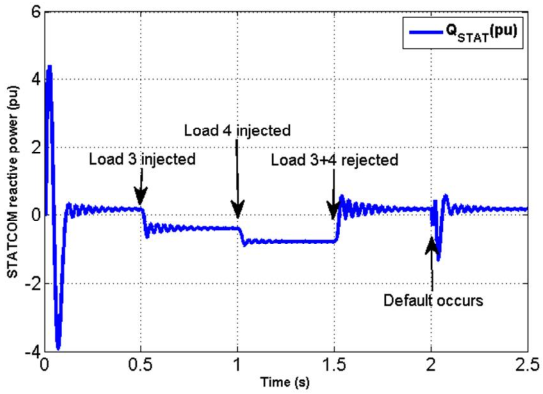

Fig. 12 STATCOM reactive power in pu

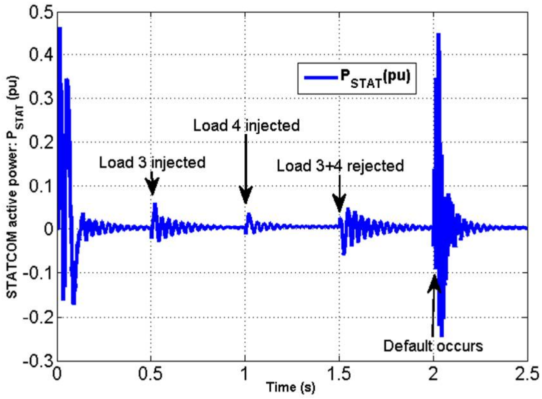

Fig. 13 STATCOM active power in pu

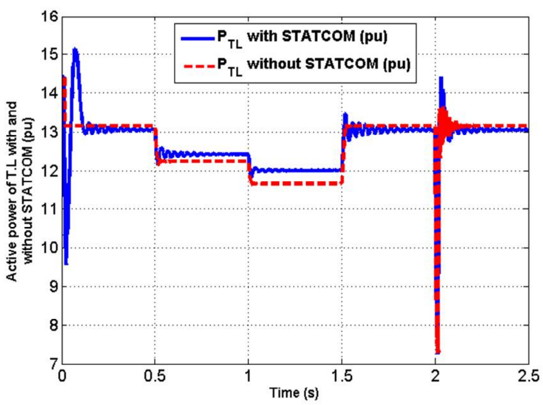

Fig. 14 Active power of transmission line in pu

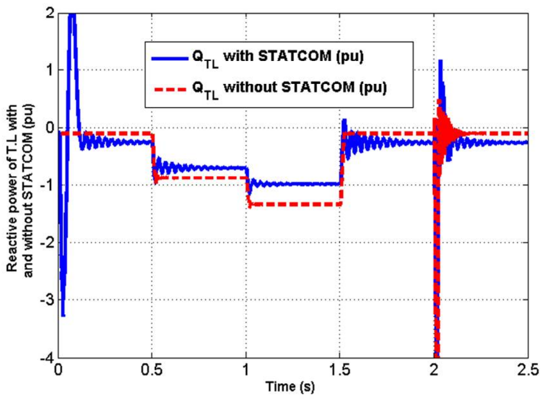

Fig. 15 Reactive power of transmission line in pu

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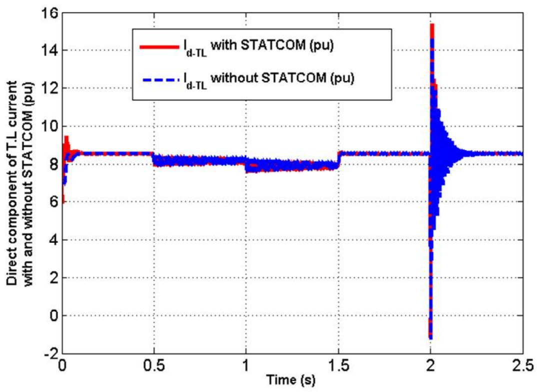

Fig. 16 Direct component of transmission line current in pu

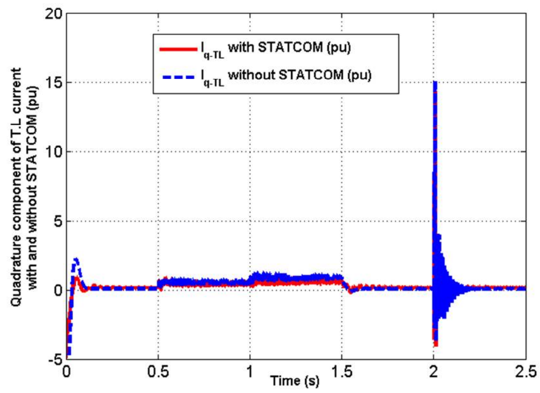

Fig. 17 Quadrature component of transmission line in pu

VI. CONCLUSION

The paper presents an original expanded 48-pulse GTO voltage source converter of a STATCOM shunted device. The implemented FACTS device has been modelled by using 4×12-pulse VSCs operating on fundamental frequency switching principle and phase angle control algorithm employing PI controllers. The control algorithm is achieved by a novel dual loop current decoupled controller using direct and quadrature STATCOM current. A detailed model of the ±100 MVAR STATCOM has been expanded and connected to the 500 kV AC power system network so as to supply the required reactive compensation.

These full descriptive digital models are simulated and validated in MATLAB environment. The performance of the shunt device is validated in both capacitive and inductive modes. Results shown could lead to the following conclusions:

- The STATCOM is able to exchange reactive power with the AC network system by absorbing or generating a rate of current equivalent to required reactive power.
- The DC voltage of the capacitor is increased or decreased by the control system such that the generated voltage has the correct amplitude for the required reactive power.
- The task of the control system is also to keep the AC generated voltage in phase with the system voltage at the STATCOM connection bus in order to generate or absorb reactive power only.
- The STATCOM compensator has allowed regular control of load voltage of the AC network system subject to many conditions and has fitted the damping to easily locate to steady state situation.
- The 48-pulse GTO-VSC enables the power factor compensation, voltage control and harmonic elimination.
- The STATCOM is able to act when AC system is facing several perturbations such as changing various kinds of loads and three phase short- circuited fault.
- The simulations demonstrate high quality of the 48 pulse STATCOM for voltage stabilization, dynamic reactive power compensation and power flow control.

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VII.APPENDIX

Parameters of the GTO-VSC based 48-pulse 3-level, 100 MVAR STATCOM model, parameters of the transmission lines, coupling transformers , connected loads and three phase AC sources are given in table I.

Table 1 Three phase AC sources parameters

Parametrs	Power Grid 1	Power Grid 2
Phase angle for phase a	0	-75
Base voltage (Kv)	500	500
Nominal power (MVA)	3000	2500
Source resistance (Ω)	0.8929	0.8929
Source inductance (mH)	16,58	16,58
X/R	8	7

Table 2 STATCOM parameters

Type of valves	GTO
Number of pulses	48
Nominal ac voltage	500 kv
Nominal dc voltage	2 kv
Rated power	100 MVAR
Total Capacitance	2500μF
Rated dc Voltage	2 kv

Table 3 Power transformer parameters

Frequency (Hz)	60
Rated power (MVA)	100
Rated voltage (kv)	500/15
Resistance (pu)	0.05
Reactance(pu)	0.05

Table 4 Transmission lines parameters

parameters	Line 1	Line 2
Frequency (Hz)	60	60
Resistance (Ω/km)	0,01755	0,0175
Inductance (mH/km)	0.8737	0.8737
Capacitance ($^{\eta F/km}$)	13.33	13.33

Table 5 Coupling transformer parameters

Frequency (Hz)	60
Nominal power (MVA)	100
Primary voltage (kv)	500
Secondary voltage (kv)	15

Table 6 Load parameters

Parameters	Load 1	Load 2	Load 3	Load 4
Active power (MW)	6,3	12,5	75	50
Inductive power (MVA)	4,7	9,4	56	37
Capacitive power (MVA)	0	0	0	0

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