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Application of Multilevel Voltage-Source-Converter in FACTS Devices for Power System Voltage Control & Reactive Power Compensation

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Abstract: *Voltage control and fast reactive power compensation are two main application area of Static Synchronous Compensator(STATCOM),which is a shunt connected voltage source converter(VSC) based FACTs controller using power semiconductor devices(particularly IGBT,GTO etc.).However, the total Statcom circuitry has complex and coupled system dynamics which require advanced controllers (specially FPGA/DSP based) to achieve well performance. In our paper, we have represented a sixty pulse VSC for producing higher pulse number by combining a twelve pulse converter with a five level VSI in order to obtain the overall performance of the said VSC in a three phase system. As the number of levels increases in the VSI of the Statcom, it will produce a staircase wave with lower value of THD. The simulation results are presented and it is observed that the STATCOM shows excellent response to step change in the reactive current reference & the value of THD is also within the acceptable limit.*

Keywords: *FACTS, Multilevel converter, Statcom, Voltage stability, Reactive Power Compensation*

I. Introduction

The field of voltage control application in power system using FACTS devices has been one of the most active areas in research & development of application of power electronics in power system as a remedy to release the extremely transmission system tension. Several generating station as well as industrial process have increased their power level needs, driven mainly by economy of scale, triggering the development of new power semiconductors, converter topologies and control methods. Amongst the power switching devices, GTO (rating ≈ 4.7 Kv) was the standard for medium voltage transmission system until the advent of high power IGBTs and gate commutated thyristors (GCTs) in the late 1990s [2]. These switching devices are now extensively used in high power application due to their superior switching characteristics, reduced power losses, ease of gate control and snubberless operation.

With the trend of de regulating power industry and installing more distributed generators, the future power system needs to provide sufficient, stable .economic, secure and high quality electric power to various load centres. It is envisaged that FACTS devices or controllers are going to play a critical role in operating the new type of power systems under such a complex operating environment [4].
FACTS technology has been expected to offer the following advantages:-

a) A major thrust of FACTS technology is the development of power electronic-based systems that provide dynamic Control of the power transfer parameters of transmission voltage, line impedance and phase angle.
b) It increases the loading capability of lines with the thermal capability.
c) Provides greater flexibility in sitting new generation.
d) To reassign power flows at will and on a real time basis.
e) To bring the transfer capability of transmission line approaching its thermal limit violating the stability criteria.

Amongst the FACTS devices, STATCOM is a new generation of reactive power compensating devices,which is much used in various power system operation and control due to its fast control characteristics as well as continuous compensating capability. The hardware of a STATCOM is similar to the shunt brunch of the Unified Power Flow Controller (UPFC) and can be controlled to provide both the real and reactive power compensations.Fig1 shows the schematic diagram of Statcom shunt FACTs controller.
As the classical two level VSIs are limited to low or medium power applications due to the device voltage limits, the series connection of switching devices enable the high power two level VSI. With the addition of few components like diodes or capacitors, permitted to enhance the quality of input and output variables, brings out the multilevel VSI (ML-VSI) technology.
This paper presents the design of a sixty pulse vsc based STATCOM, where the five level VSI is utilized as a re-injection circuit. Here sixty-pulse VSC consists of the following componenets:-

a) The standard twelve-pulses shunt converter.
b) A half-bridge diode-clamped inverter providing three-level.
c) A half-bridge inverter sharing a common split-capacitor power supply providing other two level to the dc pulse.

The proposed STATCOM is used to provide satisfactory performances in performing various reactive power flow control during transient as well as steady state operations of power systems.In order to simulate realistic conditions,.three phase power flow is so important. In our proposed model, there are three phase transmission lines unbalanced in high voltage transmission network and also there are one or two phase lines are in some distribution network. The results of various power flow control examples are presented in the matlab/simulink environment to show the successful decision of the sixty-pulse VSC based STATCOM and its effectiveness in voltage and reactive power control in power systems.

II. Aspects of availability Transfer Capability(ATC)

The reasoning behind the development of ATC is based on several principles developed by the 'North American Electric Reliability Council's(NERC)[5].ATC actually is the measurement of the transfer capability remaining in the physical transmission network for further commercial activity, over and above already committed uses.ATC must recognize time variant power flow conditions and the effects of simultaneous transfers/parallel path flow from reliability point of view. Briefly ATC can be defined as [Dobson et al.,2001].

ATC = TTC – CBM – TRM – 'Existing TC'

Where, TTC denotes the 'total transfer capability.'

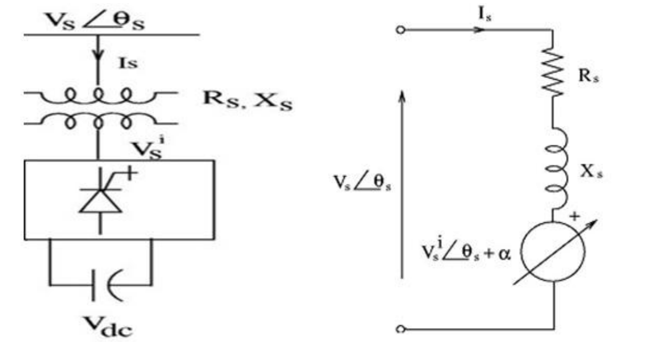
This capacity is defined by the worst contingency for the defined point-to-point path and the thermal, voltage and stability limits of the path.

CBM denotes the 'capacity benefit margin'.

TRM denotes the 'transmission reliability margin'.

III. Aspects of FACTS devices

Nowadays, centralized control of bulk power system will no longer be possible because of the development of distributed generation systems and thus traditional vertically integrated utility structures will no longer be used much. FACTS devices can provide a solution to a number of potential problems such as uneven power flow through the system, more transmission losses, lower stability margin(both transient and dynamic), sub-synchronous oscillations and greater voltage fluctuations. The majority of the FACTs topologies are designed to minimize the problems by controlling the amount and direction of reactive power (mainly) flows through the coupling transformer reactance (X), which lies between bus and VSC (Ref Fig 2).



(a) Schematic. (b) Equivalent Circuit.

Fig. 1. STATCOM shunt FACTS controller.

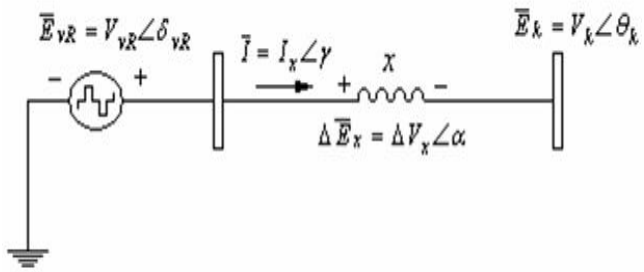


Fig. 2. Equivalent one-phase circuit of the STATCOM.

E_{vR} → Represents the STATCOM's terminals voltage.(acts as variable voltage source) and V_{vR} is a function of the STATCOM's capacitor rating.

E_k → Voltage at the power system bus,k.

Δ Ex →voltage drop in the coupling reactance, X

The incorporation of battery energy storage systems(BESS) is required into the FACTs devices to overcome the problems of uneven active power flow. transient and dynamic instability, subsynchronous oscillations and lower quality of power by proper active power control. The possibility of controlling the power flow in an electric power system without generation rescheduling or topological changes can improve the performance effectively. with increased loading of power system, combined with de regulation of power industry, motivates the use of power flow control as a very cost effective means by using power- electronics based controllers.There are several methods for finding the optimal locations of FACTS devices in both vertically integrated and unbundled power systems [7].

However, the drawback of FACTs/ESS devices, is the size of the storage systems for FACTs integration, particularly BESS may be too high for practical use in transmission-level applications. Voltage instability occurs in large battery systems, where multiple cells are placed in series. However large oscillations can be mitigated with modest power injection from a storage system, and thus it is possible to consider design for FACTs converters that take advantage of smaller voltage energy systems (SVES).Multilevel inverter can replace standard VSC to decreasing the required BESS voltage. Additionally, it can provide improved voltage quality, decreased switching frequencies, reduced power losses, decreased stress on individual switching devices, and enable more effective use of ESSs.

IV. Modeling of the STACOM with Five Level VSI

FACTS devices have the ability to allow power systems to operate in a more flexible, secure, economic and sophisticated way. When transmission constraints make certain combinations of generation and demand unviable due to the potential of outages, FACTs devices may be used to improve the system performance by controlling the power flows in the grid.

A schematic representation of a traditional six pulse (two levels) STATCOM is shown in Fig 3.

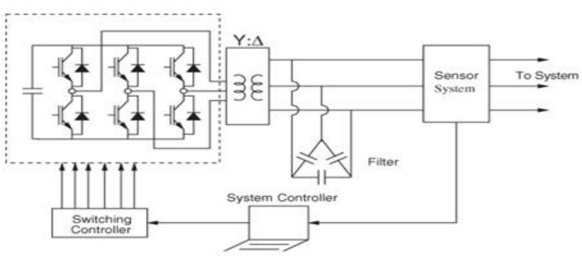


Fig 3:- Schematic of the traditional six pulses STATCOM.

It is composed of a VSC and its associated shunt connected transformer with system bus. The transformer is used as a link between the VSC and the system bus. To explain the basic principle of STATCOM,it is considered that the coupling transformer is lossless and in this way ,its equivalent one-phase circuit has already been depicted in fig 2.

In fig 2, if we take θ_k =0 as the reference, the following equations are obtained when STATCOM supplying power to the bus :-

$$\overrightarrow{E_k} = \overrightarrow{E_{vR}} - \Delta\overrightarrow{E_x}. \qquad \text{………..(1)}$$

$$P = \frac{V_{vR}V_k}{x} sin\partial_{vR} \qquad \text{………..(2)}$$

$$Q = \frac{V_{vR}^2}{x} - \frac{V_{vR}V_k}{x} cos\partial_{vR} \qquad \text{………..(3)}$$

Under normal operating conditions, to compensate for the power losses that exist in its interior, a small amount of active power must flows into the VSC. Normally there is always a slight phase difference between δ_{vR} and θ_k. A STATCOM without accompanying energy storage is used primarily for reactive power support and voltage related problems can be significantly reduced by STATCOM controlled reactive power injection. The problems of transient & dynamic stability, uneven active power flow, sub-synchronous oscillation and power quality issues can be impacted more effectively by active power control. In corpora ting an ESS, such as batteries, super conducting magnetic energy storage(SMES),fuel cells into a STATCOM device can provide dynamic decentralized active power capabilities and give transmission service providers much needed flexibility for reducing transmission level power flow problems, if the dc voltage of the STATCOM is closely regulated.

The present VSC represents sixty pulse five level inverter topology which greatly reduces the harmonic distortion on the ac side i.e. at the output side of the STATCOM as well as decreases stress on the electronic components due to decreased voltages and lower switching losses. To improve efficiency and control of VSC multilevel converter uses a variety of PWM strategies, amongst which SVPWM control strategy is very much effective. This type of inverters also reduces the size of the individual energy storage units without compromising performance. Since the dc voltage no longer requires direct control, it is possible to design controls to vary the output reactive power (or voltage) and active power independently by varying the magnitude and angle of the fundamental component of the injected current. A five level cascaded converter with unequal voltage levels can be converted into a nine level converter[8].e.g. if the batteries of the five level converter are rearranged such that dc voltage V_1 and V_2 are unequal, then a nine level stair case output voltage waveform can be synthesized.

Due to the potential for charge imbalance of the capacitors, diode clamped converters (DCMLI) are used less frequently than cascaded inverters in industrial applications. However two most recent advances in charge-balancing circuit or to use space vector modulation[19].Since a balancing circuit is required for optimal operation, several connections can be used to better utilize the STATCOM/BESS.e.g, the number of batteries can be reduced by placing them across the inner dc link capacitors. This reduced system is called a STATCOM/2BESS.

V. Optimum Location of FACTS devices

The primary function of a STATCOM is to provide voltage regulation within the power system.To provide best performance, a STATCOM should be placed at those buses which provide high voltage response for incremental changes in reactive power injection. The main objective for FACTS device placement may be one of the following:-

1.Reduction in the real power loss of a particular line.
2. Reduction in the total system real power loss.
3.Reduction in the total system reactive power loss.
4.Maximum relief of congestion in the system.

For the first three objectives, sensitivity approach of the total system reactive power loss w.r.t the control variables of the FACTs devices based methods may be used. If the objective of the placement of FACTS devices is maximum relief of congestion, the devices may be placed in the most congested lines. One means of quantifying the sensitivity in voltage magnitude to changes in reactive power is to use a voltage security indicator such as the singular value decomposition of the system Jacobian :-

$$J = U\Sigma V^T = \sum_{i=1}^{n} \sigma_i u_i v_i^T \qquad \text{……………(4)}$$

Where u_i and v_i are the columns of the $n \times n$ orthonormal matrices U and V,and Σ is a diagonal matrix of positive real singular values σ_i, so that

$$\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq \text{…………..……} \geq \sigma_n \geq 0 \qquad \text{……………..(5)}$$

The smallest singular value σ_n is an indiactor of the proximity to the static voltage limit, the right singular vector Vn corresponding to σ_n indicates the sensitive voltage magnitudes and angles and the left singular vector u_n corresponding to σ_n indicates the most sensitive direction for changes of active and reactive power injections. At the critical loading point, the relatively large elements of left singular vector u_n will correspond to those system buses, which are highly sensitive to reactive power injections. If we place the STACOM at these buses, most effective voltage regulation can be obtained.

VI. Mathematical Modeling of the STATCOM in D-Q Reference Frame

When switching functions are approximated by their fundamental frequency components, neglecting harmonics, a STATCOM can be modeled by transforming the three-phase voltages and currents to D-Q variables using Kron's transformation. The STATCOM can be represented functionally, as shown in Fig.1.Magnitude control of the converter output voltage is achieved by modulating the conduction period affected by the dead angle β of a converter while the dc voltage is kept constant. The converter output voltage can be represented in the D-Q reference frame as:

$$V_s^i = \sqrt{{V_{sD}^i}^2 + {V_{sQ}^i}^2}$$
$$V_{sD}^i = k_m V_{dc} \sin(\theta_s + \alpha)$$
$$V_{sQ}^i = k_m V_{dc} \cos(\theta_s + \alpha) \quad \text{............ (6)}$$

The following equations in the D-Q variables can be given for describing STATCOM:

$$\frac{dI_{sD}}{dt} = -\frac{R_S \omega_B}{X_s} I_{SD} - \omega_o I_{sQ} + \frac{\omega_B}{X_s}[V_{sD} - V_{sD}^i] \quad \text{............. (7)}$$

$$\frac{dI_{sQ}}{dt} = \omega_o I_{sD} - \frac{R_S \omega_B}{X_s} I_{SQ} + \frac{\omega_B}{X_s}[V_{sQ} - V_{sQ}^i]$$

------------------------- (8)

$$\frac{dV_{dc}}{dt} = -\frac{\omega_B}{b_c} I_{dc} - \frac{\omega_B}{b_c R_p} V_{dc}$$

------------------------------(9)

Where,

$$I_{dc} = -[k_m \sin(\theta_s + \alpha) I_{sD} + k_m \cos(\theta_s + \alpha) I_{sQ}] \quad \text{-----(10)}$$

I_{sD} and I_{sQ} are the D-Q components of the STATCOM current, θs is the phase angle of the bus voltage and α is the angle by which the fundamental component of the converter output voltage leads the STATCOM bus voltage Vs. km is the modulation index and for a three-level converter it is a
function of the dead angle β and is given by km = k1 cosβ, where $k^1 = k\rho$. $k = \frac{4\sqrt{6}}{\pi}$ for 24-pulse converter. ρ is the transformation ratio of STATCOM interfacing transformer. In a three level 24-pulse converter, the dc voltage reference may be adjusted by a slow controller to get the optimum harmonic performance at βoptimum = 3.75^oin the steady state.

VII. Simulink Model

In our proposed system (Fig.4), the STATCOM is connected to bus through a coupling transformer with resistance and reactance respectively. In the Power circuit diagram of the STATCOM, the converter has multipulse or a multilevel configuration. With Five level converter topology, the magnitude of the ac output voltage of VSI can be changed by varying the dead angle with fundamental switching frequency. This higher level topology of the VSI greatly reduces the THD much more than two-level VSI. Here, the Statcom is connected to a 25 KV,60 Hz.

System,where fixed load and variable loads are existing in different buses.

The STATCOM output is coupled on parallel with the network. A 12,000μF capacitor is used as dc voltage source for the inverter. The standard response time is typically chosen to be of the order of a hundred microseconds (i.e. 0.1s). To control the output voltage of VSI, PWM Strategy has been used not only for fast communications to reach a lower THD but also it can be effectively used during unbalanced operation of the system. The design of a sixty pulse VSC based STATCOM, where the five level VSI is utilized is shown below. Here sixty-pulse VSC consists of the following components :-

a) The standard twelve-pulses shunt converter.
b) A half-bridge diode-clamp inverter providing three-level.
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The proposed STATCOM is used to provide satisfactory performances in performing various reactive power flow control during transient as well as steady state operations of power systems.

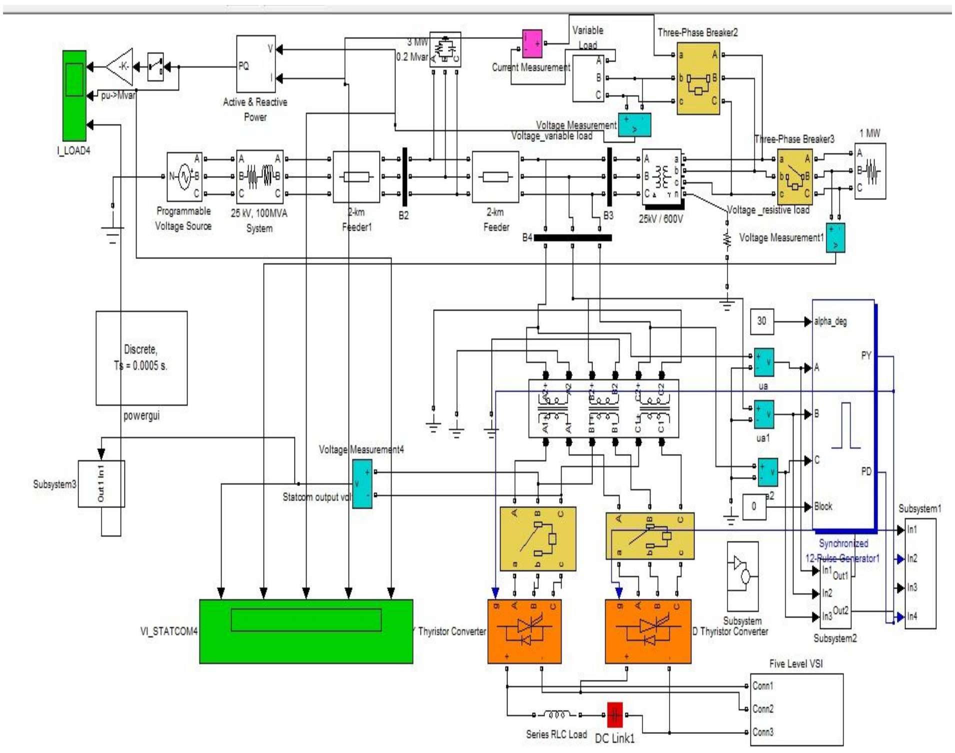

Fig 4: Proposed simulink model of 64 pulse STATCOM

Output Scope :-

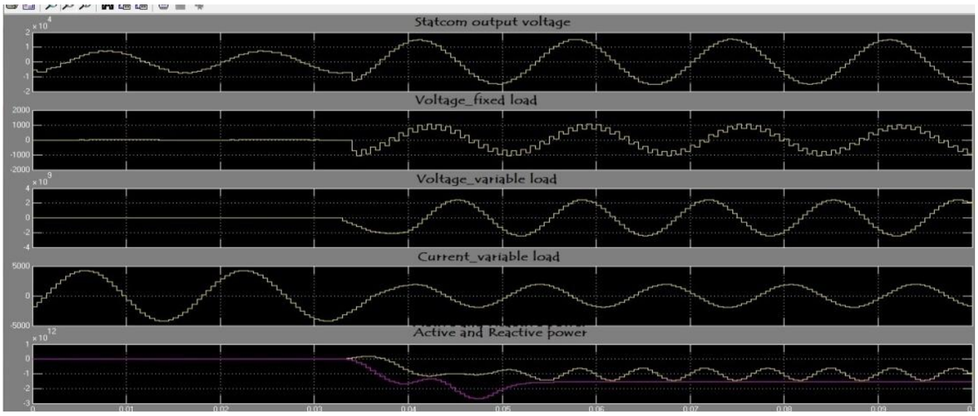

Fig 5 : Output waveforms of the simulink model.

FFT Analysis :-

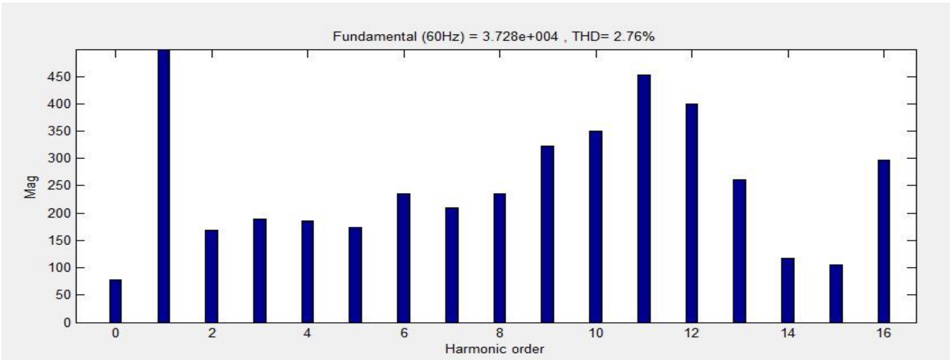

Fig6.Output Voltage waveform of Fixed Load

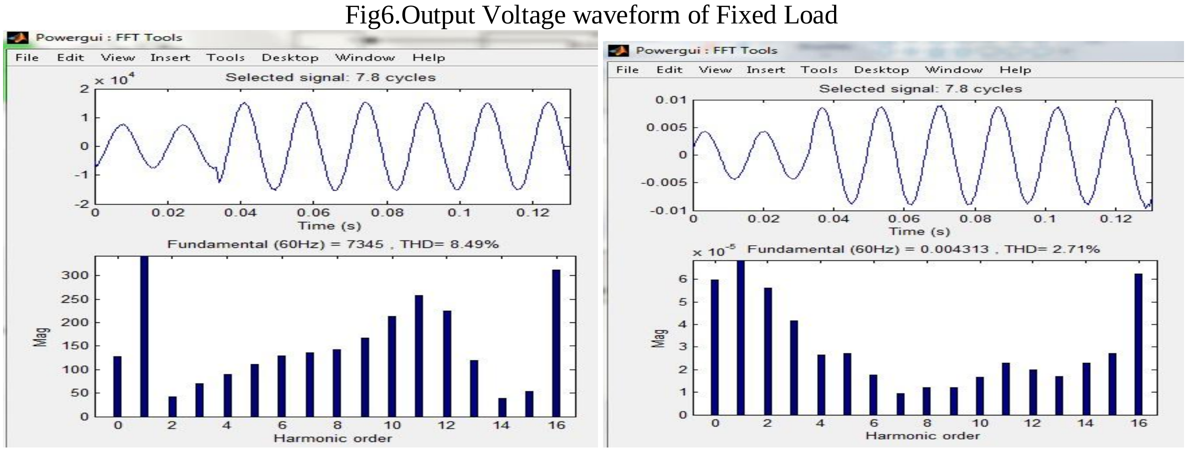

Fig 7 : Output voltage(left) and current(right) waveform of STATCOM

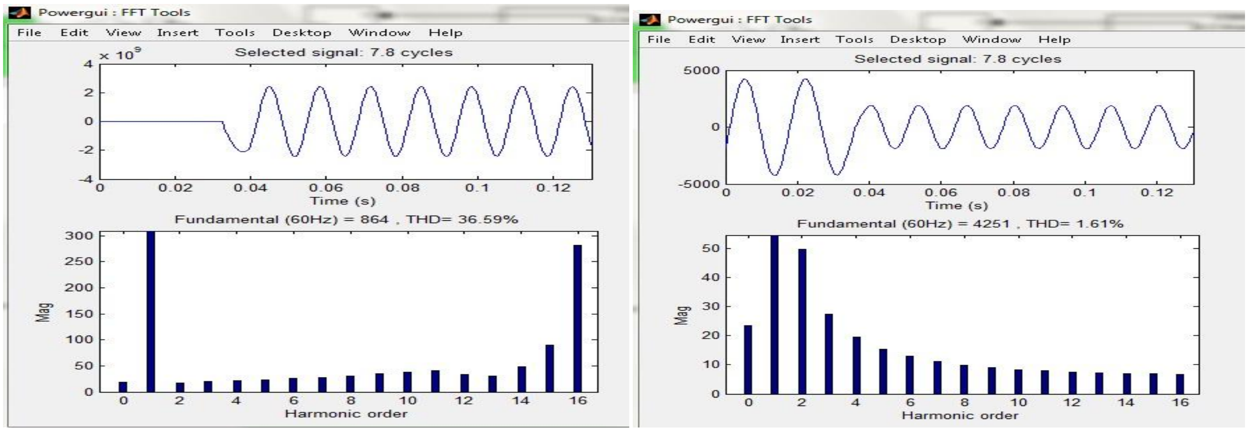

Fig 8: Output voltage (left) and current (right) waveform of variable load

VIII. Conclusion

This paper has presented the state-of-art and development of multilevel VSCs for high power rating transmission system application within the STATCOM. Due to improved dynamic performance, extended operating range, increased availability, reduced line harmonics and an adjustable power factor at the point of common coupling, multilevel VSIs are used as VSC within the STATCOM. The main feature of the proposed system and switching strategy is that it can fast modify the switching patterns of the internal power electronics switches of the given STATCOM to achieve the desired voltage across the load terminals. The mathematical modeling of the STATCOM for power system applications is also presented here. The diode-clamped converter(which provides three level part of the five level VSI) provides a large operating range and the ability to use fewer batteries with a balancing circuit. The increase of the converter power of multilevel VSCs will enable replacement of thyristor based CCVs and LCIs in the near future.

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Appendix :-

The five level VSI which has been proposed in the given simulink model is shown below :-