International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 05 | May-2016 www.irjet.net p-ISSN: 2395-0072

Modeling and Analysis of 24-pulse GTO-Based STATCOM for Voltage Regulation

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Abstract - *This paper describes the multi-pulse GTO based voltage source converter operation of a STATCOM (static compensator). In this paper, 24-pulse, 2-level ±100 MVR STATCOM operation is demonstrated. The voltage source inverter (GTO-based) is operated by a gate pulse given by the two PI-controller to trigger the GTO and twenty four pulses are generated. Here the inter-facing magnetic topology is used in two stages and with this harmonic distortions in the network is minimized to IEEE-519 permissible limits. The STATCOM model is simulated in the MATLAB environment. This model is used for the voltage regulation and power factor corrections in power system. The performance is checked against the grid connected system. The STATCOM connected system gives better voltage regulation.*

Key Words: GTO, STATCOM, Voltage regulation, Control loop

1.INTRODUCTION

A Flexible AC Transmission System (FACTS) is an AC transmission system incorporating power electronic-based or other static controllers which provide better power flow control and enhanced dynamic stability by control of one or more AC transmission system parameters (voltage, phase angle. and impedance) The STATCOM is traditionally modeled for power flow analysis as a PV or PQ bus depending on its primary application. The active power is either set to zero (neglecting the STATCOM losses) or calculated iteratively. [1-4]

The STATCOM voltage and reactive power compensation are usually related through the magnetic of the STATCOM. This traditional power flow model of the STATCOM neglects the impact of the high frequency effects and the switching characteristics of the power electronics on the characteristics of the power electronics on the active power losses and the reactive power injection (absorption) [4-6]. The STATCOM used to regulate voltage and to improve dynamic stability. It is composed of inverters with a capacitor in its dc side, coupling transformer, and a control system. The inverters are, in conventional STATCOMs switched with a single pulse per period and the Transformers are connected in order to provide harmonic minimization. The equipment action is made through the continuous and quick control of capacitive or inductive reactive power [7]. Its output voltage is a waveform composed of pulses that approaches a sinusoidal wave.

2. STATCOM & ITS OPERATING PRINCIPLE

Per phase equivalent circuit is shown in Figure1. Where VG is ac source voltage, VC is STATCOM output voltage, Ic is the current drawn by STATCOM and LT is transformer leakage inductance and `RT' is the resistance that represents the losses of the system [8-11].

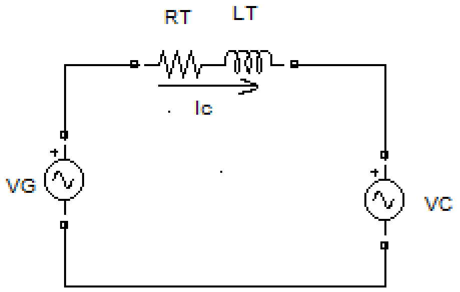

Fig -1: Equivalent circuit diagram of STATCOM [1]

The STATCOM is basically a DC-AC voltage source converter with an energy storage unit, usually a DC capacitor. It operates as a controlled Synchronous Voltage Source (SVS) connected to the line through a coupling transformer. Fig. 1 shows the Equivalent circuit diagram of STATCOM. The controlled output voltage is maintained in phase with the line voltage, and can be controlled to draw either capacitive or inductive current from the line in a similar manner of a synchronous condenser, but much more rapidly. STATCOM has the ability to maintain full capacitive output current at low system voltage, which also improving the transient stability.

Basically, a STATCOM output voltage always contains harmonics, due to the switching behavior of the VSI. These voltage harmonics will generate harmonic currents and further cause power losses in the system network. If the impedance of the lines that connect a STATCOM to the power system is neglected, the harmonic losses are primarily apparent on the connection transformer. The effect of these losses in the transformer can by analyzed by considering an expansion of the transformer. [8]

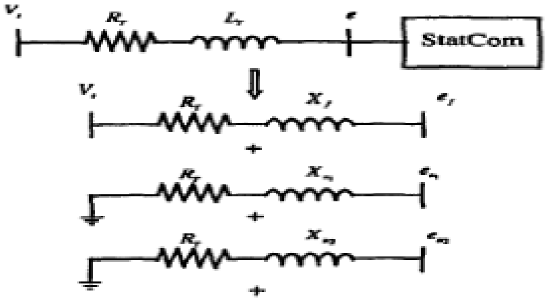

Fig -2: STATCOM Model for Harmonic losses

Fig.2 shows the circuit of a STATCOM connected to a power system by a connection transformer, where V and e represent the system RMS voltage and the STATCOM's RMS output potential respectively, and RT and XT denote the resistance and leakage reactance of the connection transformer. Assuming that there are not any harmonics in the system voltage V, the STATCOM output voltage e consists of fundamental and high-order harmonics, and may be represented as:

e = ef+ en1+en2 (1)
e = ef + ∑ ei (2)
i= n1, n2...

Where ef, is the RMS value of the fundamental harmonic, ei, represents the RMS values of high-order harmonics, and n1, n2 are the harmonic indices. Thus, the first diagram of Fig 2 can be represented as the sum of the other harmonic diagrams.[8]

Ploss = Pfundamental + Pharmonic (3)

(a) CONTROL OF REACTIVE POWER

It is well known that the amount and type (capacitive or inductive) of reactive power exchange between the STATCOM and the system can be adjusted by controlling the magnitude of STATCOM output voltage with respect to that of system voltage. The reactive power supplied by the STATCOM is given by Equation below:-

Q = (Vstatcom-Vs)/X (4)

Where VSTATCOM, and Vs, are the magnitudes of STATCOM output voltage and system voltage respectively and X is the equivalent impedance between STATCOM and the system. When Q is positive, the STATCOM supplies reactive power to the system. Otherwise, the STATCOM absorbs reactive power from the system.

(b) CONTROL OF DC CAPACITOR VOLTAGE

If all the components were ideal and the STATCOM output voltage were exactly in phase with the system voltage, there would have been no real power exchange between STATCOM and system therefore the voltages across the DC capacitors would have been able to sustain. However, a slight phase difference between the system voltage and the STATCOM output voltage is always needed to supply a small amount of real power to the STATCOM to compensate the component loss so that the DC capacitor voltages can be maintained. This slight phase difference is achieved by adjusting the phase angle of the sinusoidal modulating signal. If the real power delivered to the STATCOM is more than its total component loss, the DC capacitor voltage will rise, and vice versa. The real power exchange between STATCOM and the system is described by Equation (5) below:-

$$P = \frac{V_{S-}V_{STATCOM}\,Sin\delta}{X} \qquad (5)$$

Where δ is the phase angle difference between STATCOM voltage and the system voltage.

A controllable three-phase AC output voltage waveform close to sinusoidal nature is obtained at the point of common coupling (PCC). The output AC voltage of the VSC(Voltage source converter) is (Vc) is governed by a DC capacitor voltage (Vdc), which can be controlled by varying phase difference (α) between Vc and Vs (supply voltage). An almost sinusoidal current in quadrature with the line voltage is injected into the electrical system emulating an inductive or a capacitive reactance at PCC. The magnitude of the quadrature component of the VSC current (Iq) regulates the phase difference (α) between Vc and Vs across the transformer leakage reactance (X), which in turn controls reactive power flow, Here α is basically is the firing angle. The basic operating principle of a GTO-VSC based STATCOM is that When Vc>Vs, the STATCOM is considered to be operating in a capacitive mode and when Vc < Vs, it is operating in an inductive mode and for Vc = Vs, no reactive power exchange takes place and STATCOM is said to be operating in floating mode. However, a small phase difference (α) is maintained so that VSC losses are compensated by active power drawn from AC system. Applying phase angle control (α) between Vc and Vs, Vdc is controlled with charging or discharging of the capacitor and thus capacitive or inductive or floating mode of operation is emulated to control reactive power flow in the AC system.

3. SIMULATION AND OPERATION OF STATCOM

In this paper the concept of new magnetics is evolved to eliminate 5th, 7th harmonics in first stage and in the second stage 11th, 13th and higher order of voltage harmonics and thus, minimizes the THD levels. Inter-facing magnetic is configured in two stages by employing a combination of 3-phase Δ-Y/Y converter transformer in first stage and a group of two 3-phase PSTs for +15º and -15º phase shifts in the second stage. The two sets of phase-shifted voltage waveforms and output ac voltage waveform from the converter transformer are added electromagnetically to get final output voltages at the point of common coupling (PCC).

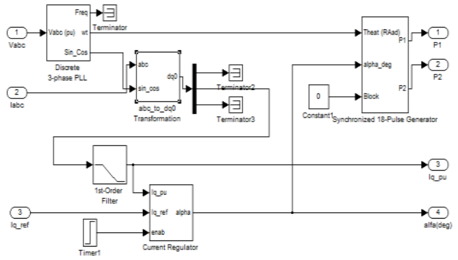

Fig -3: Inner current control loop circuit

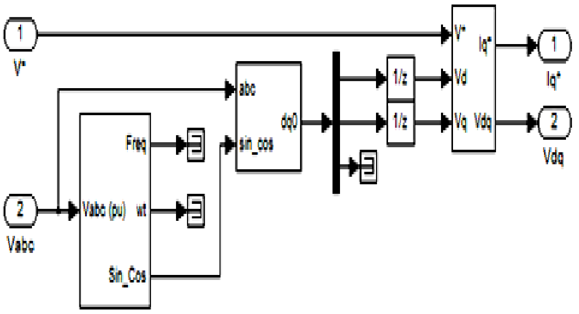

Fig -4: Outer voltage control loop circuit

CONTROL OF STATCOM

The controller of a STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that the STATCOM generates or absorbs desired VAR at the point of connection. Fig. 5 shows a simplified diagram of the STATCOM with an inverter voltage source and a tie reactance, XT1E, connected to a system with a voltage source, VTH, and a Thevenin's reactance, XTH , When the inverter voltage is higher than the system voltage, the STATCOM sees" an inductive reactance connected at its terminal. Hence, the system "sees" the STATCOM as a capacitive reactance and the STATCOM is considered to be operating in a capacitive mode. Similarly, when the system voltage is higher than the inverter voltage, the system "sees" an inductive reactance connected at its terminal. Hence, the STATCOM sees the system as a capacitive reactance and the STATCOM is considered to be operating in an inductive mode.

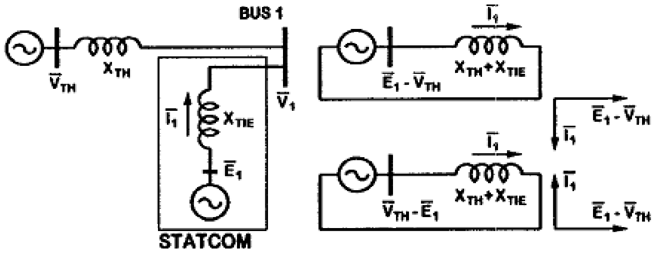

Fig -5: Static Synchronous Compensator Operated in Capacitive and Inductive Modes.

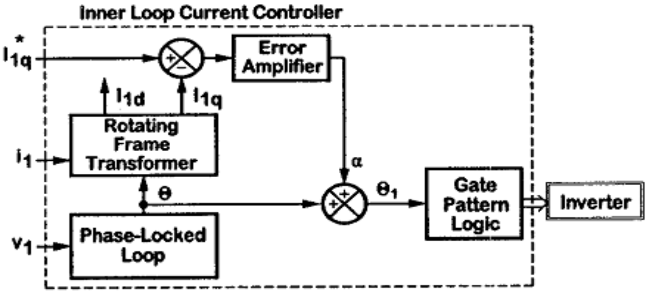

Fig -6 Current Control Block Diagram of a Static Synchronous Compensator.

Fig. 6 shows the reactive current control block diagram of the STATCOM. An instantaneous 3-phase set of line voltages, v1, at BUS 1 is used to calculate the reference angle, θ, which is phase- locked to the phase a of the line voltage, v1a An instantaneous 3- phase set of measured inverter currents, i1 is decomposed into its real or direct component, I1d and reactive or quadrature component, I1q respectively. The quadrature component is compared with the desired reference value, I1q* and the error is passed through an error amplifier which produces a relative angle, α of the inverter voltage with respect to the line voltage. The phase angle, θ1, of the inverter voltage is calculated by adding the relative angle, α of the inverter and fig.4 shows the MATLAB/Simulink system of inner current control loop.

The outer voltage control unit maintains the voltage across the dc capacitor equal to a constant reference voltage. Keeping the dc voltage constant simplifies the voltage control scheme shows in fig.4. This control loop system generates the reference current Iq reference and injected in the inner current control loop which further generates the firing angle α for the GTO-based converter and also generates a voltage Vdq; voltage at the dq co-ordinates.

Transformer connection:-

The transformer connection used in 24-pulse STATCOM model used to eliminates the 5th,7th harmonics in first stage and in the second stage 11th, 13th and higher order of voltage harmonics and thus, minimizes the THD levels. Inter-facing magnetics is configured in two stages by employing a combination of 3-phase Δ-Y/Y converter transformer in first stage, and a group of two 3-phase PSTs for +15º and -15º phase shifts in the second stage shows in fig.7.

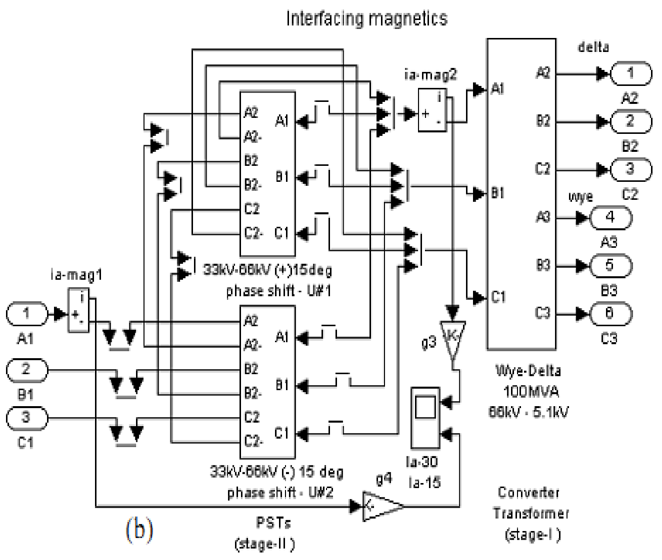

Fig -7: Transformer connection for Phase-shifting.

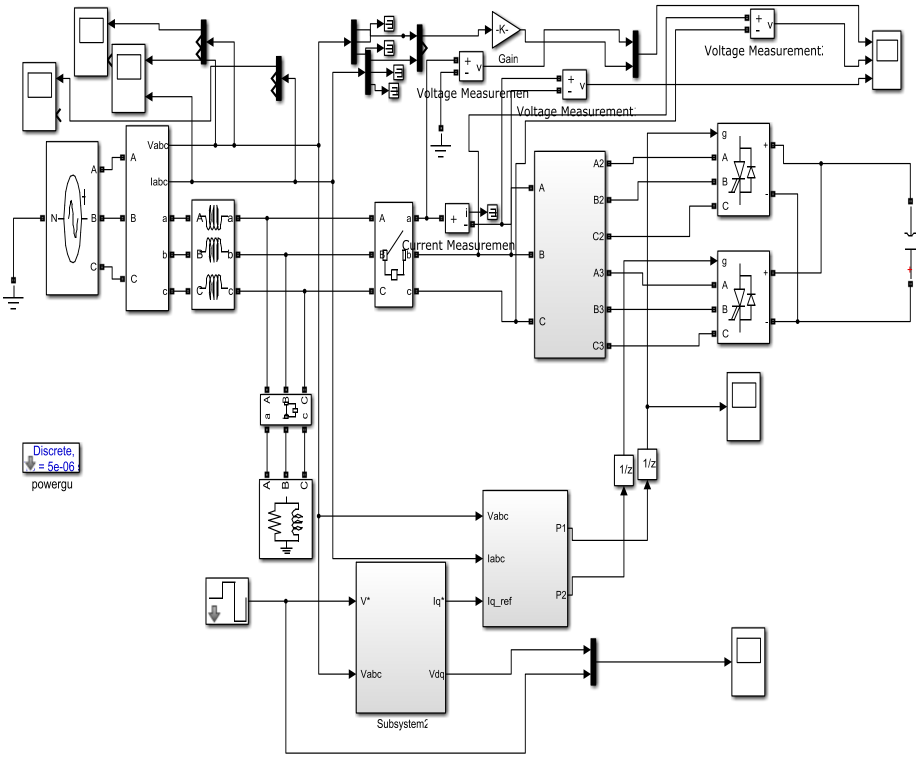

Fig -8: 24-Pulse STATCOM Model.

4. RESULTS

The reference line voltage V* is set to 1.0pu, 1.03pu, 0.97pu and 1.03pu at the instant of 0s, 0.22s, 0.42s, 0.60s respectively. In the voltage control loop presuming that STATCOM would be operated as a voltage regulator. With the DC capacitor (C) pre-charged and total simulation time set at 0.60sec, the performance of the compensator corresponding to a load of 70MW 0.85pf (lag) at 132kV is studied.

The voltage waveform is shown in fig.9. From the fig. 9 the variations in the voltage can be clearly seen. In fig.10 shows the voltage at the point of common coupling (PCC). The STATCOM injects the reactive power when the voltage is less than the reference value and vice-versa. The voltage and current spectrum is shown in fig.11 at the point of common Coupling (PCC). The harmonic spectrum for voltage regulation corresponding to the capacitive and inductive mode for voltage and current are shown in figure 10(b), figure 11(b) (For capacitive mode), FFT analysis on the voltage and current harmonic spectrum have been carried out for the compensator and THD levels quantified during its operation for voltage regulation and power factor correction to unity.

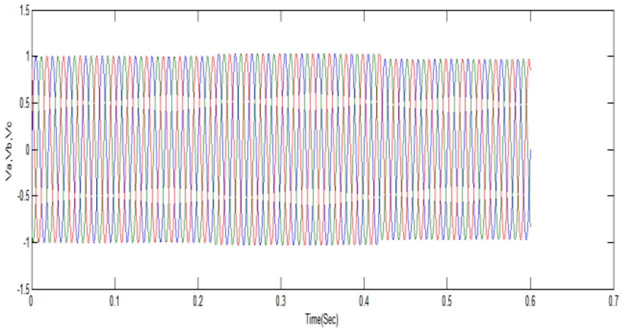

Fig -9: Three phase instantaneous voltages.

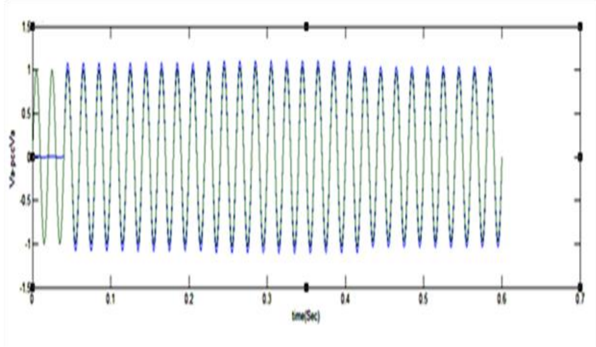

Fig -10(a): Voltage at PCC.

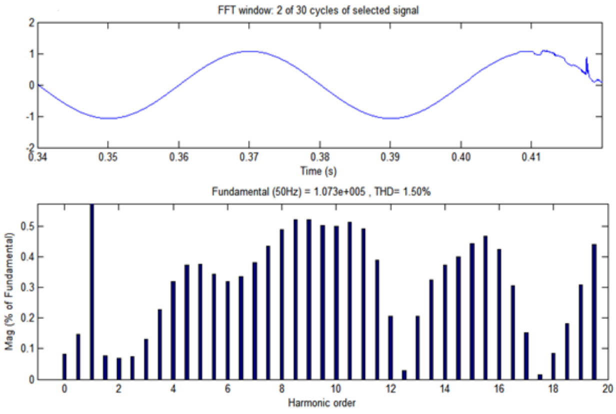

Fig -10(b): Voltage (Va) Spectrum in Capacitive mode

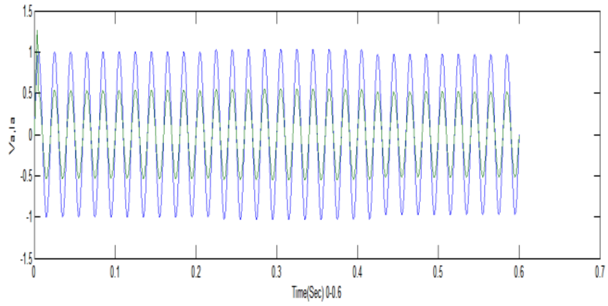

Fig -11(a): VaIa at PCC

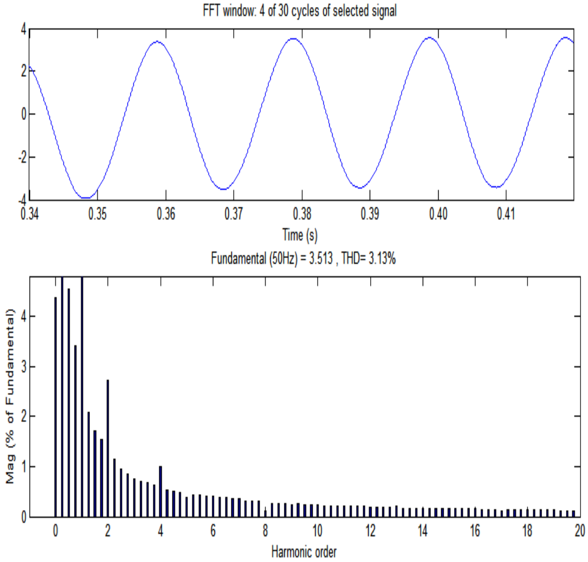

Fig -11(b): Current (Ia) spectrum in capacitive mode

5. CONCLUSIONS

A new type of multi-pulse STATCOM having two stages of magnetic circuit is evolved. The first stage of magnetic circuit is used for setting-up VSC output AC voltage to line voltage level, while other magnetic circuit is used for providing phase shift to the output voltage of stage-1 magnetic circuits, which in turn sets an electromagnetic coupling with AC system at PCC (Point of Common Coupling). These magnetic circuits are also work to mitigate the harmonics of the order of 5th, 7th, 11th, 13th and higher order. This model is designed with two elementary 6-pulse GTO-VSCs connected in parallel across the DC capacitor used as energy storage, and interfacing magnetics configured in two stages. It also contained the tow PI-controllers, one of them is named as inner current control loop and another is outer voltage control loop. The compensator has been simulated to regulate voltage for an inductive load in electrical network as well as power factor correction to unity. Basic operating characteristics of the model as illustrated shows it's satisfactory and improved performance.

As we have seen the performance of STATCOM working as voltage regulation mode as well as unity power factor correction var control mode. And by seeing the results of THDs of voltage and current spectrum we can say that STATCOM performs much better while working in voltage regulation mode as compare to the unity power factor correction in var control mode. Although unity power factor correction in var control mode gives satisfactory results but voltage regulation mode of operation mode improve the performance of the STACOM, and is greatly accepted in industrial and power utility applications.

6. APPENDIX

Parameters of the GTO-VSC based 24-pulse 2-level ± 100 MVAr STATCOM model:

1) STATCOM parameter:
Converter type-VSC; Thyristor-GTO; no. of pulses-24; normal AC voltage-5.1Kv;normal DC voltage-8.3 kv; GTO fixed resistance-0.01Ω GTO triggering control – fundamental frequency (50Hz) switching DC capacitor - 20000μf.

2) Interfacing magnetic (Base-100MVA):
Stage-1
- Converter transformer:

3-phase 3-winding PST
Rating: 1000MVA,50Hz,66Kv/5.1kv,12.8 % (X)
Vector group: Y/Δ-Y
Stage- II
- 3-phase 3winding zigzag connected (+)15degree

Rating: 100MVA,50Hz,66kV/5.1Kv,12.8 % (X).
Stage –II
- 3-phase 3- winding zigzag connected(+) 15 degree PST Rating: 25 MVA,50 Hz,33 kv/5.1kv, 10.8%(X),Vector Group: Zigzag or interconnected-star/open-Y
- 3-Phase,3-winding zigzag connected(-15) degree PST ,Rating:- 25 MVA,50 Hz,33 kv/5.1kv,10.8%(X) Group: Zigzag or interconnected-star/open-Y

3) PI-controller Gains:-

Inner Current Controller:-Kp =29, Ki=2000
Outer Voltage Controller: - Kp =70, Ki=1500

4) Thevenin equivalent Voltage Source:-
Nominal Voltage:-132 kv(rms); Fundamental frequency-50Hz, Short ckt. Level: - 3000 MVA; X/R ratio-10

5) Transmission Line:-
R=0.1622Ω, L=1.0214e-3H

6) Discrete Sampling Time =5e-6s
7) MATLAB Version-2011

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