

COURSE 5:- EMTP TOOL MODEL SIMULATION & INSULATION COORD AND POWER ELECTRONICS

1.0 EMTP TRANSIENT STUDIES CONCEPT & USAGE OF PSCAD

1.1 INSULATION COORDINATION OVERVIEW

- Standard lightning impulse, switching impulse, TOV withstand voltages as per IEC & IEEE standards
- Overview of standards related to overview of insulation coordination, transients, modelling of power system components, transient stability, low frequency, switching transients, fast transients, lightning over and very fast transients overvoltage voltage, and power electronics switching.
- Concept of equipment nominal and impulse over voltage
- Control & mitigation of overvoltage's
- Concept of transit time and propagation voltage or current wave incident, reflection and refraction and calculation of their factors for use in creation of Bewley lattice diagram or wave bounce diagrams
- Concept of distributed series and shunt L & C model with low calculation time step for transit time and space effect of travelling voltage and current wave.
- Steps in insulation coordination analysis as per IEC/IEEE
- Space & time wave travel and transit time effect on selection of location of surge arrester for lightning protection of major cost electrical equipment like Transformer excel calculation of location
- Surge protection covering basics of surge arrester selection, surge arrester voltage rating, nominal, low and high impulse discharge current rating, residual discharge voltage. Surge arrester protective level, surge arrester current withstands level and pressure relief class.
- Line lightning surge energy discharge calculation based on surge impedance and critical line insulation flashover voltage and surge propagation transit time considering speed of travel of electrical wave over ai insulation line.
- Cable switching surge energy discharge calculation based on surge impedance and critical line insulation flashover voltage and surge propagation transit time considering speed of travel of electrical wave over ai insulation line.
- Surge arrester rated voltage and TOV rating selection based on different source system neutral earthing methodology.

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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- Equation Of Lightning Impulse Wave
- Circuit breaker restriking voltage-TRV & RRRV
- Motor surge protection calculation due to lightning propagation through transformer interwinding capacitance even with surge arrester
- Overview of calculations in system with series resonance, series & parallel resonance as well as parallel resonance due to cable capacitance and & source fault reactance

Basic overview of switching transients in PSCAD by PSCAD model and simulation of simple example circuits

- **NORMAL AND FAULTED SWITCHING TRANSIENTS**
 - Closing a CB/Switch (on zero or peak point of voltage wave) on an inductive circuit, and a capacitive circuit and on a circuit with a combination of both.
 - Deenergising or opening of a CB/Switch in an inductive circuit, and a capacitive circuit and on a circuit with a combination of both.
 - Closing of inductor & capacitor in parallel & resulting closing CB/Switch (on zero or peak point of voltage wave) revealing zero current missing phenomenon when cb is closed at peak of voltage wave.
 - Energizing a long length of HV cable (for example 75 km at 132 kV) at zero or peak point of voltage wave
 - Closing of shunt reactor & cable in parallel & resulting closing CB/Switch depicting zero current missing phenomenon
 - Tripping of 75 km 132 kV cable for CB terminal fault with source including transformer and other cables on common bus.

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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- **ABNORMAL SWITCHING TRANSIENTS**
 - Effect of CB current chopping and re-ignitions due to multiple restrikes during inductive circuit switching (same as de-energizing of 132 kV shunt reactor) with discussion of reactor CB current chopping and re-strike effects
 - TOV & TRV due to de-energizing and multiple restrikes with trapped charge in capacitor (cable)
 - Effect of CB de-energizing and re-striking on actual HV cable model
- **TRANSFORMER INRUSH/ENERGIZING STUDY**
 - Normal transformer energization
 - Harmonic resonance over-voltages during transformer energizing (for receiving end transformer end)
 - Energisation of 132/33 kV 90 MVA transformer at cable receiving end with transformer modelled with saturation and remnant flux.
 - Energisation of 132/33 kV 90 MVA transformer at cable receiving end with transformer modelled with higher knee point voltage and reduced flux.
 - Ferro resonance during switching of cable connected transformer
- **GIS SWITCHING VERY FAST TRANSIENT OVER VOLTAGES**
 - Very fast transient over voltages, caused by dielectric breakdowns. due to GIS disconnector switching at 132 kV Cable sending end without & with trapped charge:
 - Very fast transient over voltages, caused by dielectric breakdowns. due to GIS disconnector switching at 132 kV shunt reactor.
 - Very fast transient over voltages, caused by dielectric breakdowns. due to GIS disconnector switching at 132 kV transformer
- **TRANSIENTS DUE TO ELECTROMAGNETIC WAVE PROPAGATION**
 - PSCAD and EXCEL BEWLEY LATTICF manual calculation for comparison of incident and reflected wave at cable end under various terminal conditions such as a short circuit or open circuit or a inductive reactance or capacitive reactance

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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1.2 EMTP TOOL PSCAD BASIC MODELLING AND PSCAD USAGE TRAINING

This will cover:

- Introduction to the different windows in the PSCAD interface
- Introduction to the pre-requisites of PSCAD operation
- Introduction to PSCAD simulations with simple RL, RC and RLC circuit switching transients and LC oscillation circuit
- Introduction to standards. (IEEE C37 011 1994 & IEEE 399 1997) and reference books to model AIS and GIS switchgear component stray capacitances, transformer inter winding capacitance, isolator / CB across pole capacitance, selection of CB disconnecter (close & open), earth switch, CT, PT, bushing capacitance and pi-sections of bus runs as required for high frequency switching and lightning studies.
- Single line and 3-line diagram simple AC circuit for circuit transient simulation case build up in PSCAD with application of circuit normal and faulted switching as well as lightning transients.
- Breaker and time break logic block as well as Fault & timed fault logic block
- Multiple Run component and related statistical analysis
- Optimal runs and related statistical analysis
- Circuit breaker TRV basic conceptual circuit and studies using PSCAD on simple circuit. Including TRV envelop generator from the library of PSCAD
- Statistical distribution of single pole breaker operation
- Harmonic Current & voltage spectrum and distortion measurement and Impedance measurement
- Introduction to Capacitor Switching Study – the different scenarios
- Concept of transformer inrush and its implications.
- Concept of frequency dependent and Bergeron models for
- Transformers and Transformers Saturation modelling for switching simulation in PSCAD (Jiles Atherton model, Basic hysteresis model)
- Modelling of Transmission Line and Tower model (and review of solved R, X, B output files) for simulation in PSCAD.

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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- Modelling of Underground Cable Models (and review of solved R, X, B output files) for simulation in PSCAD.
- Synchronous Machines Governors, Exciters modelling and usage in PSCAD
- Induction motor start transient modelling and usage in PSCAD
- Surge Arrester modelling and application, Validation of surge arrester model with data sheets.
- Active and reactive load modelling, Modelling of voltage dependency for the loads
- Single and 3 phase system as voltage behind source impedance modelled as ideal or R or L or R-L/R and validation of the source modeling
- Introduction to I/O devices in PSCAD and the instances of using them
 - Slider
 - Control parameter selection switch
 - Safety parameter selection switch
 - Output chemicals for plot
- One line & 3line wire representation of networks
- Usage of Wires and its shortcuts
- Modelling of Inductor, Resistor & Capacitor – in both static and variable manners
- Modelling of grounding and neutral inversion assessment in PSCAD on system with NER resistance selected based on system capacitance during internal fault in equipment with reactance in series with single phase earth fault causing huge voltage rise in healthy phases
- Modelling of Nodes & Bus
- Data labels and Meter components for instantaneous ampere & voltage.
- Multi meter for measuring P, Q, V, I & data tap & data merge
- Constants & gain
- Graph Frame, XY plots, control panel output channels for plot measure voltage
- Transformer OH line, Line meter, cable & Cable interface
- 2 windings, 3 windings, 4 windings, 5 windings UMEC model of transformer
- Modelling of zig zag and other earthing transformer

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- Control system and elements covering comparator, transfer functions and math / trigonometric function blocks (CMSF function blocks)
- Logical blocks usage.
- Creation of events using sequencers
- Usage of Radio links transmitter and receiver in PSCAD
- Creation of modules in PSCAD
- Transmission line charging simulations and the different scenarios needed to be simulated
- Cable charging simulations and the corresponding case simulations to be simulated

1.3 THEORY OF BASIC CIRCUIT TRANSIENT BEHAVIOUR WITH PSCAD SIMULATION OF BASIC CIRCUITS FOR THEORY SUPPORTED WITH PSCAD USAGE CONCEPT

- Transit time and traveling wave phenomena in overhead line and cable and calculation of reflection and refraction factor at junctions/ terminations to calculate incident, reflected and refracted wave and their effects on switching and lightning overvoltage.
- Speed on travel propagation and surge impedance of overhead line and cable.
- Inductance and Capacitance Circuit transients
- LC circuit switching simulation at various instants on point of source voltage wave
- L, C, LC, RC circuit switching transients.
- Inductive circuit current chopping and transient over voltage and restrike and reignition resulting in fast front voltage values that can destroy equipment insulation, OV mitigation measures such as location of surge arrests and RC surge suppressor or surge capacitors at sending and/or receiving end of supply cables to highly inductive equipment
- Insulation coordination overview covering
 - IEC & ANSI IEEE standards

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- Protective Margins.
- Principles, Objective & Methodology of Insulation Coordination
- Understanding standard lightning and switching impulse test wave and the Insulation strength base such as Basic Impulse Insulation Level as well as Switching impulse withstand level of all substation components.
- System Voltages & Over voltages
- Temporary Over voltages & Switching Over voltages, Lightning Overvoltage & Back Flashovers
- Classification of Overvoltage's such as Temporary overvoltage, Slow-front overvoltage, Fast-front overvoltage and very fast-front overvoltage.
- Temporary overvoltage & Switching overvoltage, Lightning Overvoltage & Back Flashovers
- Travelling Waves
- Very Fast Transient over voltages (VFTO) due to switching operation of GIS (Gas Insulated Switchgear) disconnecter switch opening and restrike caused due to dielectric breakdowns leading to number of pre- or restrikes that occur due to the relatively slow speed of the moving contact. VFTO act as travelling waves and propagate within and external to the GIS. Due to the travelling wave nature of the VFT the GIS elements should be modelled as electrical equivalent circuits composed of distributed parameter cables/lines (defined by surge impedance and travelling. The multiple refractions and reflections of these surges at impedance discontinuities within the enclosures create complex waveforms (very fast transient over voltages – VFTO).
- Concept of Ferro resonance overvoltage occurring due to asymmetric switching of circuit breaker poles (1 or 2 CB poles stuck during switching on fault or deenergising or energising or abnormal switching with current chopping) of OHL or underground cable connected to Delta Star 3– phase transformer under light load conditions. When nonlinear inductance of the transformer core and the capacitance of the transmission or cable network

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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are equal, ferro resonance happens. This equality can occur when the transformer is accidentally energized and de-energized in only one or two phases. Ferro resonance results in a high current and voltage across the inductance core and leads to the damage of the transformer Mitigation of overvoltage.

- Abnormal switching steep switching surges due to current chopping (typically of magnitudes 3 to 10 A), during interruption of inductive circuits like transformer by vacuum or SF 6 circuit breaker (CB).
 - ✚ Restrike of the vacuum or SF6 CB interrupting contacts, or a quick re-closing on to trapped charges of a power system, may also cause such surges.
 - ✚ Abnormal switching surges tend to be fast rising and of very short duration with a front time as short as 0.1 us or less (IEC 6007 I - I). These surges severely stress the equipment winding since they will not be uniformly applied across the windings and appears only across a small part of the winding (the line end coil or the first coil) leading to equipment damage by such steep fronted transient voltage surges.
- Mitigation of various types of over voltages.
- Surge Protection with Surge Arrestors and its selection as well as assessment of surge capacitor/RC surge suppressor.
- Need of surge arrester as part of insulation coordination for lightning over voltage protection
- Surge arrester selection criteria in respect of its rated voltage, minimum continuous over voltage, 1 sec and 10 second TOV rating for different system neutral earthed systems.
- Surge arrester VI characteristics, its protection margin and evaluation its location distance with major equipment for maximum protection.

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- Temporary over voltage associated with earth fault circuit breaker first pole to clear factor during EF, Earth Fault Factor, Temporary power frequency over voltage during EF, sudden load throws off and ferro resonance.
- CB TRV understanding and rate of rise of voltage and its impact of failure of equipment insulation.
- System neutral earthing and earth fault factor during earthing fault and provisions required to control EFF to not greater than 1.732.
- Understanding on transformer inrush and voltage dip as well as harmonic resonance over voltages.
- Insulation Coordination and Transient Modelling & Examples

2.0 TYPICAL MODELLING AND EMTP STUDIES TRAINING IN PSCAD

2.1 OVERHEAD LINE (OHL) LIGHTNING IMPULSE STUDIES COVERING.

- Direct Stroke lightning on OHL Phase Conductor
- Back flashover when lightning strikes on OHL tower shield wire

2.2 TEMPORARY OVER-VOLTAGE STUDIES ASSOCIATED WITH

- L-G fault
- Sudden load shedding
- Ferro resonance

P.Nandakumar, C-203 Akshata Apartments, Tilak Nagar Building No. 1, P.O Tilak Nagar, Chembur Mumbai 40089. email: nanda57@gmail.com; Mobile:- +919821871436

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2.3 TRANSFORMER SWITCHING STUDIES.

- Normal energizing studies at selected point on voltage wave.
- Magnetising Inrush switching studies at selected point on voltage wave with various remnant flux in transformer.
- Multiple run point of voltage wave closing at multiple points in preselected range and interval from voltage zero crossing to determine optimum point of closing as far as reduced voltage dip or current inrush is concerned. Optimum run will be determined using Multirun component in PSCAD.
- Normal de-energizing studies at selected point on voltage wave.
- Abnormal transformer opening with current chopping leading to reignition and multi restrikes.
- Faulted and fault clearance switching for assessment of TRV & RRRV

3.0 SWITCHING OVER VOLTAGE STUDY CASES IN TRAINING USING PSCAD

3.1 OVERHEAD TRANSMISSION LINE SWITCHING

- Line modelling using.
 - Bergeron Model using wave transit time effect and line surge impedance.
 - PI modelling with R L C constants. Multiple PI in multiple series PI for long lines
 - Frequency dependent model using line modelling with conductor geographic layout and conductor type. Review Line solved positive and zero sequence R, XL, B constants and compare with PSSE/DiG SILENT
- Compare steady state load flow and fault results in PSCAD as well in PSSE and Dig SILENT for consistency check.

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- Line switching surge over voltage studies using all modelling techniques for comparing results of each.
 - Line energization studies at zero point of voltage wave and at peak of voltage point.
 - Line energisation with multiple run point of wave closing angle for $\frac{1}{2}$ cycle to determine optimum point of closing as far as voltage or current inrush is concerned. Optimum run will be determined using Multirun component in PSCAD.

- Line de-energisation surge overvoltage studies using all modelling techniques for comparing results of each covering.
 - Line de-energization studies at zero point of voltage wave and at peak of voltage point.
 - Line de-energisation with multiple run point of wave closing angle for $\frac{1}{2}$ cycle to determine optimum point of closing as far as voltage or current inrush is concerned. Optimum run will be determined using Multirun component in PSCAD.
 - Line de energization at various points on voltage wave.

- Faulted Line tripping studies, under LLL, LLLG, LG, LLG, LL faults at sending, receiving and few locations along line length, using all modelling techniques for comparing results of each covering.
 - Line de-energization studies due to faults at various point on wave of voltage using multi run to assess the maximum voltage across the first opening contact pole of the tripping breaker to assess CB TRV & RRRV for comparison with corresponding permissible TRV & RRRV limits as per IEC & IEEE standard.

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- Ferro resonance over voltage study of line connected to delta star transformer during line energisation, line opening, fault switching or current chopping with one or two pole of switching circuit breaker stuck during switching.
- Very Fast Transient over voltages (VFTO) due to switching operation of GIS (Gas Insulated Switchgear) line feeder disconnecter switch opening and restrike modelled using IEEE guidelines, caused due to dielectric breakdowns leading to number of pre- or restrikes that occur due to the relatively slow speed of the moving contact.
- Lightning strike studies on overhead tower line based on IEEE Guidelines for Modelling and Analysis of System Transients using Digital Programs. These covers
 - ✚ Back flashover due to lightning strike on tower causing tower top potential rise (based on tower footing resistance of 20ohm) and insulator flashover causing lightning surge to divert to the live conductor The back flashover strike impulse (at terminal end line distance $X_p = 2$ towers = 600m in Annex F of IEC 60071-2) will be an 4/80 μ s impulse current with a peak of 200 kA as per IEEE guideline.
 - ✚ Direct stroke/ Shielding failure: - The lightning in this case will be struck on phase conductor of OHL at terminal end side line distance of $X_p = 1$ span = 300m in Annex F of IEC 60071-2. The strike impulse will be modelled as an 8/20 μ s impulse current with a peak of 20 kA as per IEEE guideline.
- Parameters to monitor for the simulations

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4.0 UNDERGROUND CABLE SWITCHING

- Cable modelling using.
 - Bergeron Model using wave transit time effect and Cable surge impedance.
 - PI modelling with R L C constants. Multiple PI in multiple series PI for long Cables
 - Frequency dependent model using Cable modelling with conductor geographic layout and conductor type. Review Cable solved positive and zero sequence R, XL, B constants and compare with PSSE/DiG SILENT
- Compare steady state load flow and fault results in PSCAD as well in ETAP and/or PSSE for consistency check.
- Cable switching surge over voltage studies using all modelling techniques for comparing results of each.
 - Cable energization studies at zero point of voltage wave and at peak of voltage point.
 - Cable energisation with multiple run point of wave closing angle for $\frac{1}{2}$ cycle to determine optimum point of closing as far as voltage or current inrush is concerned. Optimum run will be determined using Multirun component in PSCAD.
- Cable de-energisation surge overvoltage studies using all modelling techniques for comparing results of each covering.
 - Cable de-energization studies at zero point of voltage wave and at peak of voltage point.
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- Cable de-energization at various points on voltage wave
- Faulted Cable tripping studies, under LLL, LLLG, LG, LLG, LL faults at sending, receiving and few locations along cable length, using all modelling techniques for comparing results of each covering.
 - Cable de-energization studies due to faults at various point on wave of voltage using multi run to assess the maximum voltage across the first opening contact pole of the tripping breaker to assess CB TRV & RRRV for comparison with corresponding permissible TRV & RRRV limits as per IEC & IEEE standard.
- Ferro resonance over voltage study of line connected to delta star transformer during cable energisation, line opening, fault switching or current chopping with one or two pole of switching circuit breaker stuck during switching.
- Very Fast Transient over voltages (VFTO) due to switching operation of GIS (Gas Insulated Switchgear) cable feeder disconnecter switch opening and restrike modelled using IEEE guidelines, caused due to dielectric breakdowns leading to number of pre- or restrikes that occur due to the relatively slow speed of the moving contact.

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5.0 RESTRIKING, REIGNITION, VOLTAGE ESCALATION IN TRANSFORMER/ MOTOR INDUCTIVE CIRCUIT CURRENT CHOPPING DUE TO VACUUM CIRCUIT BREAKER

- Surge impedance model of inductive transformer and motor circuits with VCB restrike and reignition model for simulation of 3 to 10 A VCB current chopping to assess CB restrike with high di/dt related reignition resulting in multiple restrikes and reignition causing multiple over voltage stakes with fast rise time on motors leading to equipment failure
- Selection of RC surge suppressor.
- Repeating study with source end and/or receiving end over voltage protecting surge arrester and RC surge suppressors that reduces the restrike over voltage phenomena

6.0 HARMONIC STUDY IN PSCAD & IN RMS SOFTWARES LIKE DiG SILENT/ ETAP

- Power system harmonics Concepts and its effects
- IEEE & IEC Standards
- Harmonic analysis studies to analyse the current and voltage harmonic levels and check if these levels comply with the contractual or international standard limits.
- Types of analyses, covering:
 - current and voltage harmonic distortion analysis, in which the individual and total current and voltage harmonic distortions are calculated at the various buses then the results are compared with the relevant contractual limits.
 - impedance versus frequency analysis, in which a plot of the system impedance at various buses is plotted against the frequency. This predicts the system resonances. A peak at in the impedance plot indicates a parallel resonance while a valley in the impedance plot indicates a series resonance.
 - Introduction to different methods of harmonic calculation
- Steps required to perform a harmonic study.

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- Production of harmonics, characteristic harmonic currents
- Effect of harmonic currents on impedance(s)
- Calculation of Total & Individual Voltage Harmonic Distortion
- Transformer thermal & K factor
- Sources of harmonics, 3 phase and 1 phase power electronic converters, UPS, lighting, VFDs, SMPS used in instruments and personal computers, HVDC transmission stations, FACTS devices such as STATCOM and static Var compensators, battery charger systems, ac and dc arc furnaces, renewable energy inverter-based generation sources
- Harmonics and system power factor systems with linear loads, with nonlinear loads with harmonics, true power factor and displacement power factor the effect of loading on harmonic current distortion and total harmonic voltage distortion (V_{thd})
- Influence of source impedance and kVA on harmonics. Influence of "stiff" and "soft" sources
- Resonance and conditions under which resonance occurs, series and parallel resonance, prevention of resonance and the effect of adding a detuning reactor.
- Evaluation of possibilities of resonance on electrical system under lowest short circuit operating condition.
- Mitigation of harmonics.
- Model zigzag transformer to assess mitigation of dc offset in wave as well as all triple harmonics
- Location of filters such as local to nonlinear load, centralised location at nonlinear load centre, Global harmonic mitigation concerned with meeting the Grid PCC harmonic limits. This allows circulation of harmonics within the plant electrical network which will be subjected to harmful harmonic impact.
- effect of phase diversity on harmonic currents, phase shifting, active filtering, zero sequence mitigation of triplen harmonics on four-wire single-phase systems, passive LC and damped filters, transformer phase shifting (multi-pulsing), active front ends" for ac converters for renewables and drives.

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- calculation of harmonic voltage distortion, manual calculation of voltage distortion, PSCAD / DiG SILENT / ETAP software estimation of harmonic distortion
- Provision of information on harmonics, information to be requested from vendors, information to be included with a harmonic analysis report.

7.0 POWER ELECTRONIC SWPM, SVPWM, CURRENT HYSTERESIS SWITCHING CONVERTER MODEL COVERING FOLLOWING

- Overview of power electronic converters and their components including electronic switching and storage devices like inductor and capacitor
- Operation and characteristics of switching devices, rectifiers, dc-dc converter and inverters
- Current conducting and voltage blocking V-I characterisers 4 quadrant operation regimes of electronic switches ie diode, thyristor, Power BJT. MOSFET, IGBT and composite switches with antiparallel or anti series diodes
- LC, LCL, filter design overview
- DC DC converter building block overview and modelling in PSCAD for open loop and closed loop control of output voltage based on varying Duty factory with switching pulse derived using carrier wave of high frequency for comparison with reference signal with amplitude modulation index. These models will cover DC DC buck converter, boost converter and buck boost converter
- Full bridge inverter model controlled by a set of square wave inputs to simulate and observe Fourier series and Total Harmonic Distortion (THD) of the output voltage and current.
- Over view of open loop power circuit and closed loop dq voltage and current feedback outer and inner controllers and PLL for generation of gate pulses required grid following PV & WTG & BESS inverter active and reactive current output to grid (based on active and reactive power set points control derived based on PV MPPT or manually derived values.)
- Grid follower inverter (PV or WTG or BESS) model in closed loop with power plant controller, voltage ride through and current limit controller for simulation and study of dynamic grid code compliance studies covering fault ride-through capability and

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post-fault recovery, reactive capability at connection point, active power regulation at connection point, high and low voltage ride through capability, frequency ride through, frequency withstand capability, voltage droop verification and validation, frequency droop verification, fault ride-through capability and post-fault recovery, voltage phase angle testing, reactive control operation, active power response based on frequency variations, rate of change of frequency, phase jumps, power oscillation damping verification for the specified frequency ranges as per, active power recovery and dynamic voltage support

- Closed loop Voltage source converter model with power and dq quantity closed control system for simulation of
 - Voltage or reactive power control distribution static compensator D-STATCOM
 - Voltage or reactive power control distribution static compensator SVC with reactor and capacitor
 - Voltage balancing and Active Harmonic mitigating active harmonic filter
 - Voltage sag or swell mitigation series FACTS dynamic voltage restorer (DVR),
 - #rd harmonic and DC offset mitigation in non linear loads with Zig Zag transformer mode and simulation
 - Variable frequency drive with motor dynamic modelling

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