भारतीय प्रौद्योगिकी संस्थान काशी हिन्दू विश्वविद्यालय

INDIAN INSTITUTE OF TECHNOLOGY
BANARAS HINDU UNIVERSITY

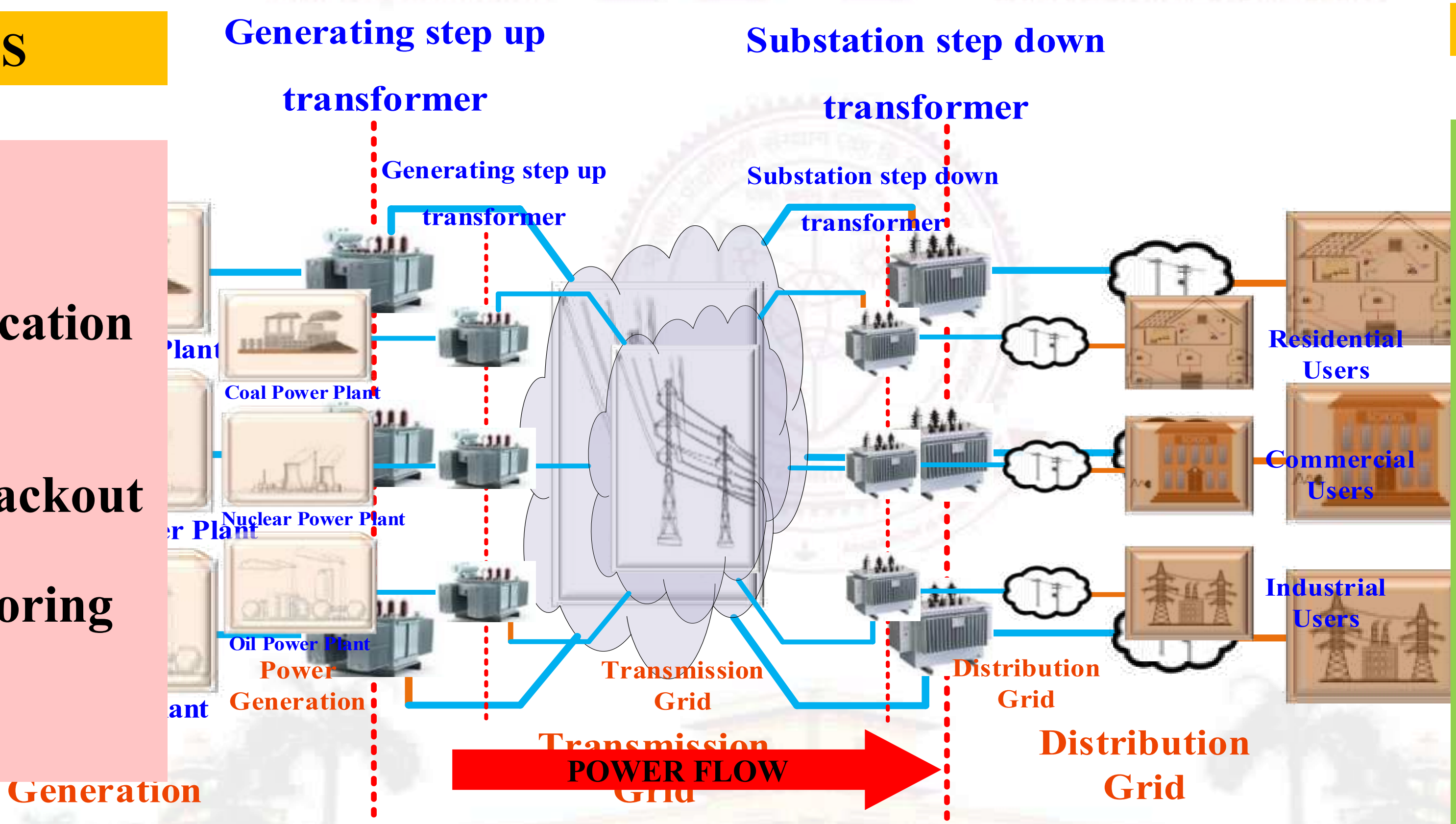
# Cyber-Resilient Smart Grid Systems: Impact of Electric Vehicle Charging, Standards and Protocols

**Prof. R. K. Singh**
**Department of Electrical Engineering, IIT (BHU) Varanasi**
rksingh.eee@iitbhu.ac.in

# Conventional Power Grid Architecture

## CHALLENGES

- ⊗ Unidirectional
- ⊗ Less communication network
- ⊗ Failure and blackout
- ⊗ Manual monitoring
- ⊗ Low efficiency



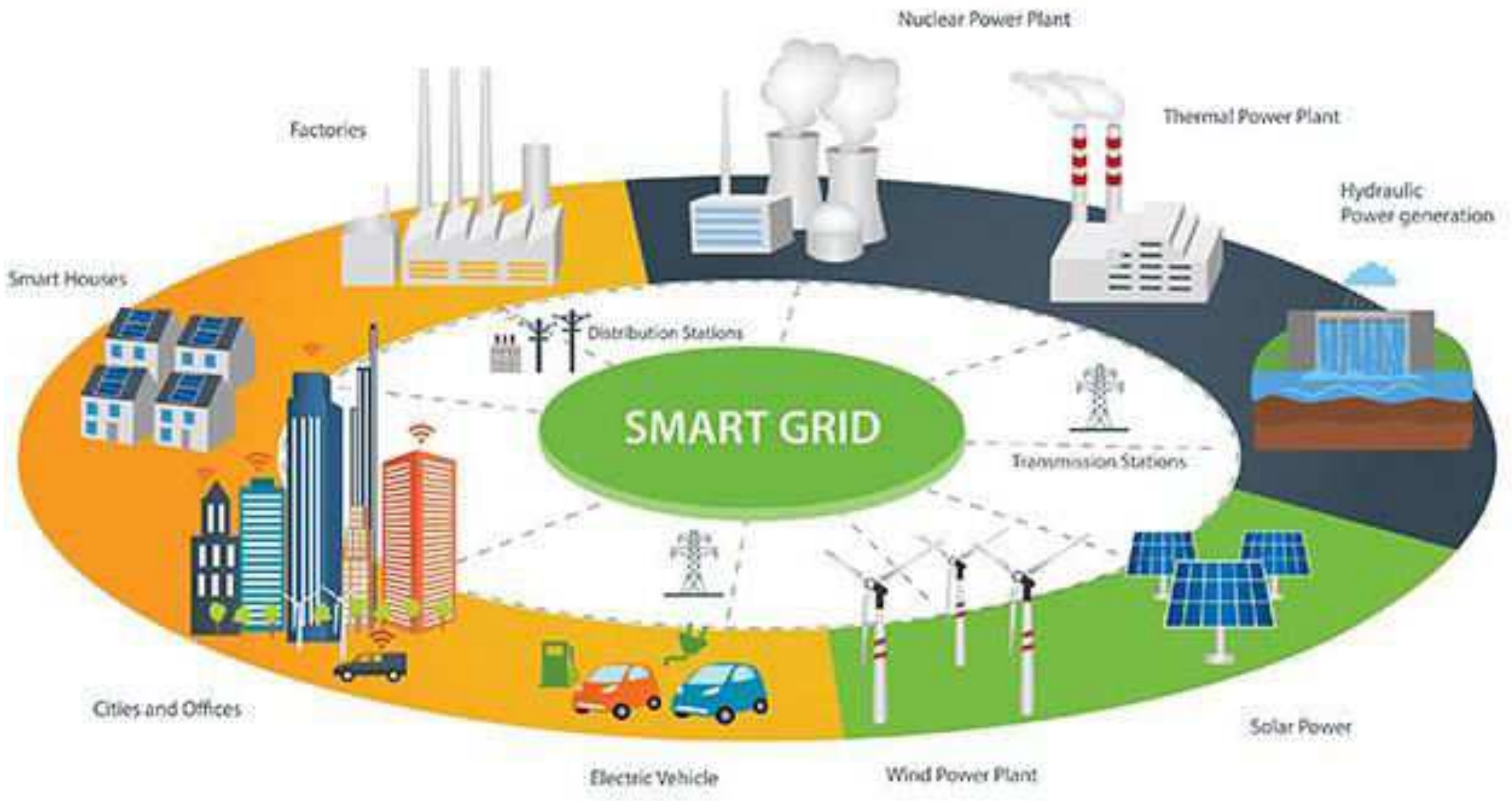

Conventional Power Grid Architecture

## SOLUTIONS

- ✓ Bidirectional power flow
- ✓ Communication rich network
- ✓ Resilient network
- ✓ Automatic monitoring (sensor dominated network)

**Solution-at-Large: Distributed Generation and Inverter based resources for control and optimization**

# Smart Grid Architecture




Smart Grid Architecture

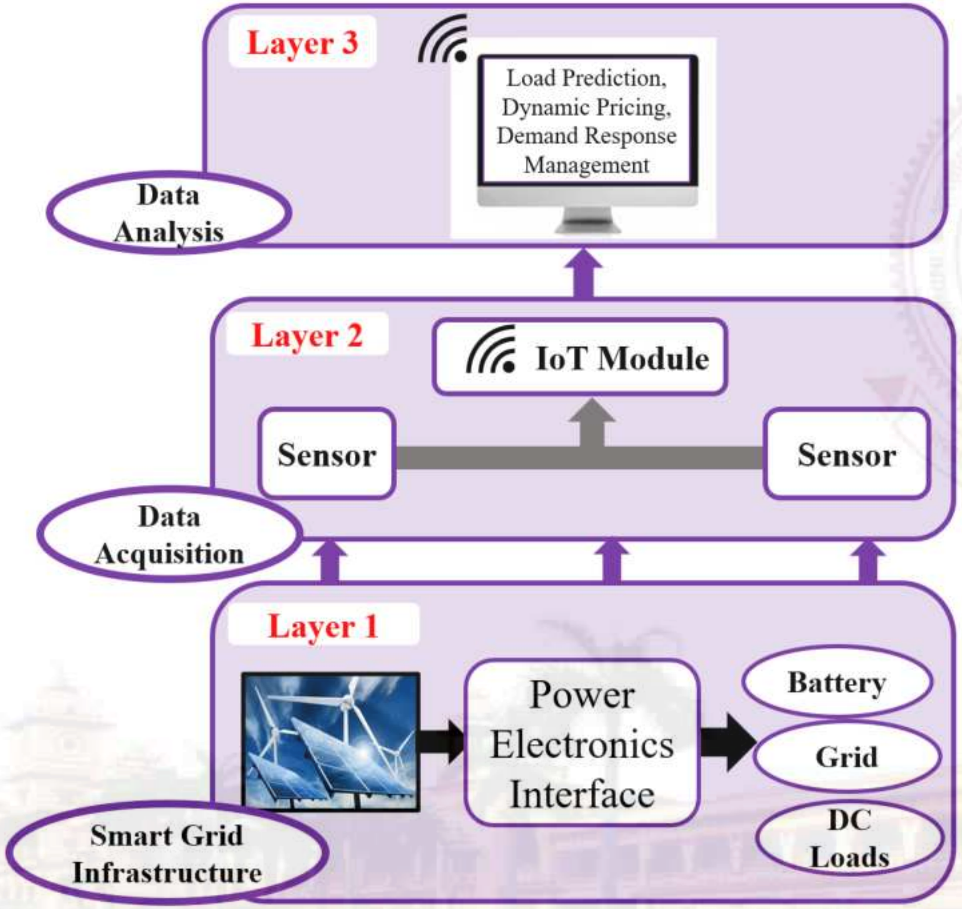
## Today's Necessity

- Clean Energy adoption
- Sustainability
- Carbon Neutrality
- Distributed Network
- Self healing

## Resilient System

Source:- https://www.123rf.com/photo_55999602_smart-grid-concept-industrial-and-smart-grid-devices-in-a-connected-network-renewable-energy-and.html

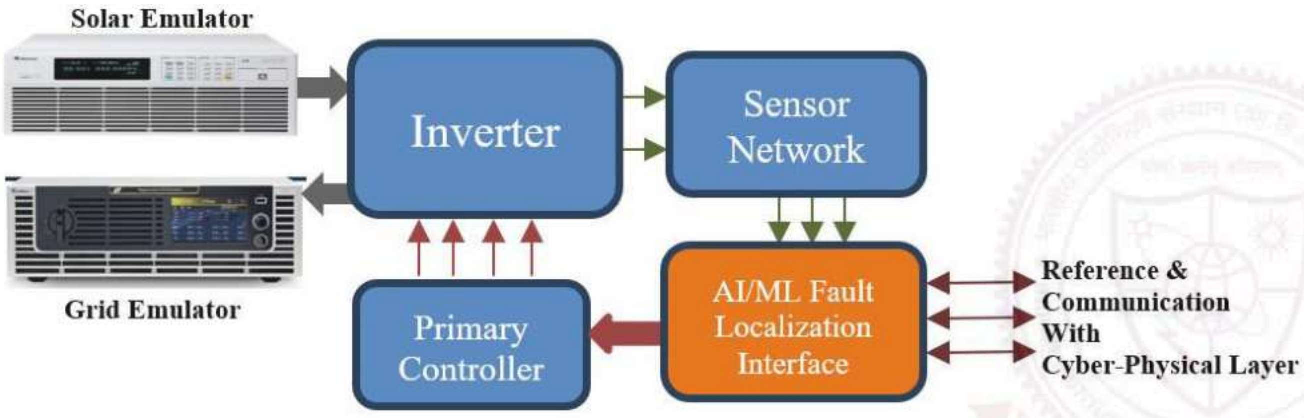
# Cyber Physical System Integration for Smart and Resilient Grid Architecture



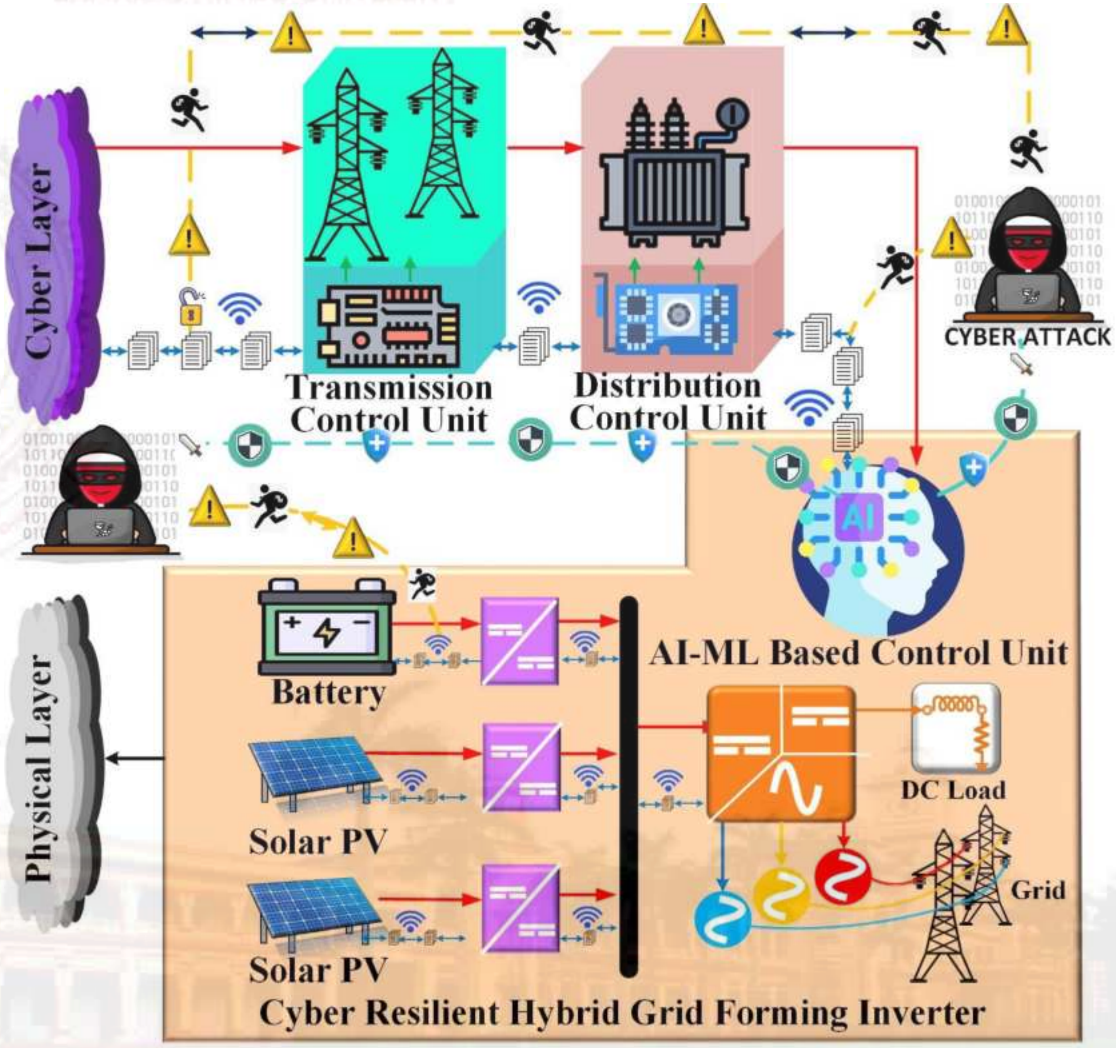

**Layered architecture of CPS for smart and resilient grid**

- **What:**
  - Distributed energy resources/load
  - Advanced sensors
  - IoT module
- **Why:**
  - For ensuring its reliability and secure operation in the face of dynamic challenges
- **How:**
  - Proactive measures to mitigate potential vulnerabilities
  - Implementation of robust encryption protocols
  - Continuous monitoring systems
  - Effective incident response plans

# Inverter Rich Smart Grid with CPS




Physical layer for enabling cyber resiliency

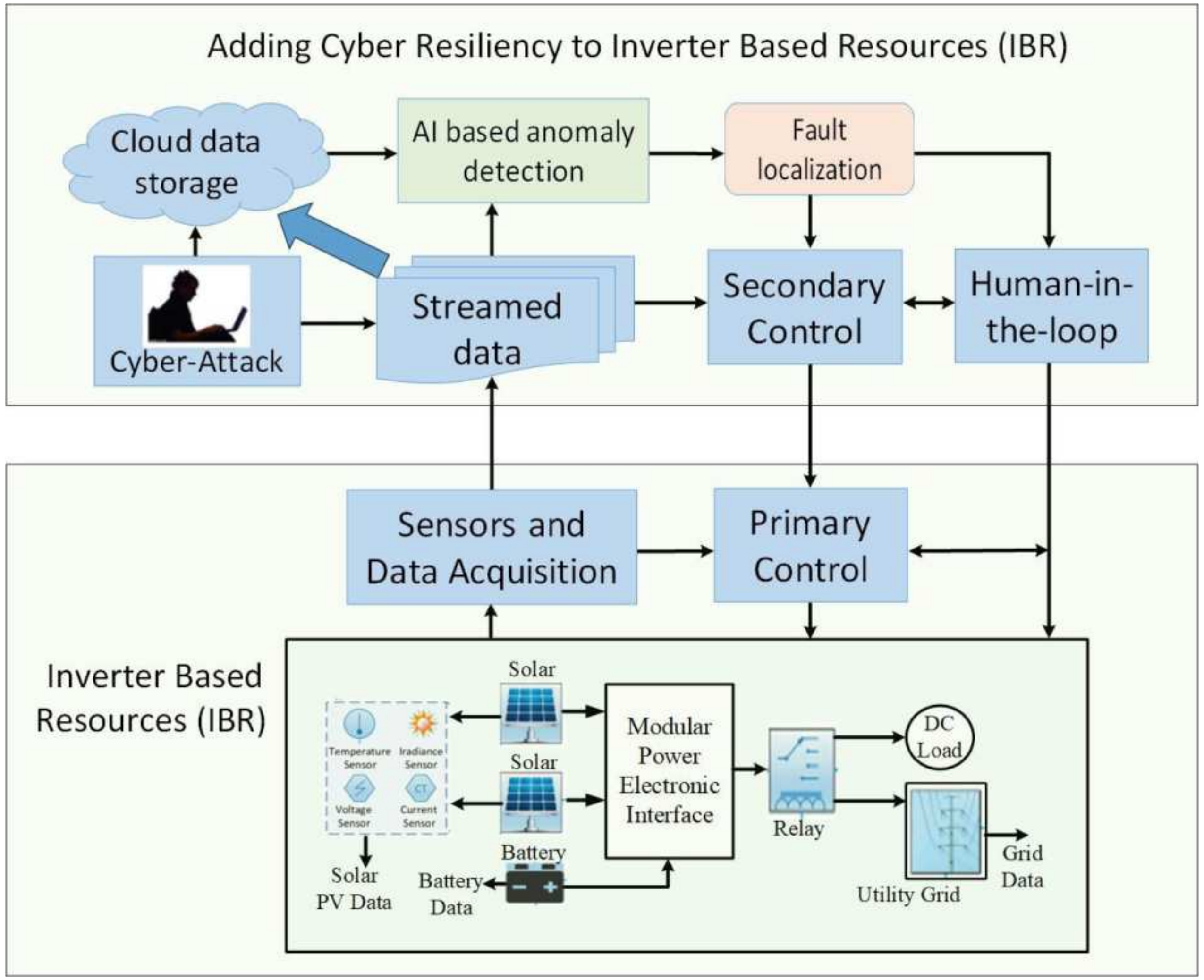



Cyber physical inverter based smart grid

## Objectives:

- Enhanced Efficiency and Reliability
- Integration of Renewable Energy
- Demand Response
- Grid Resilience
- Data-driven Decision Making
- Cost Optimization

# Cyber resilient inverter rich smart grid architecture



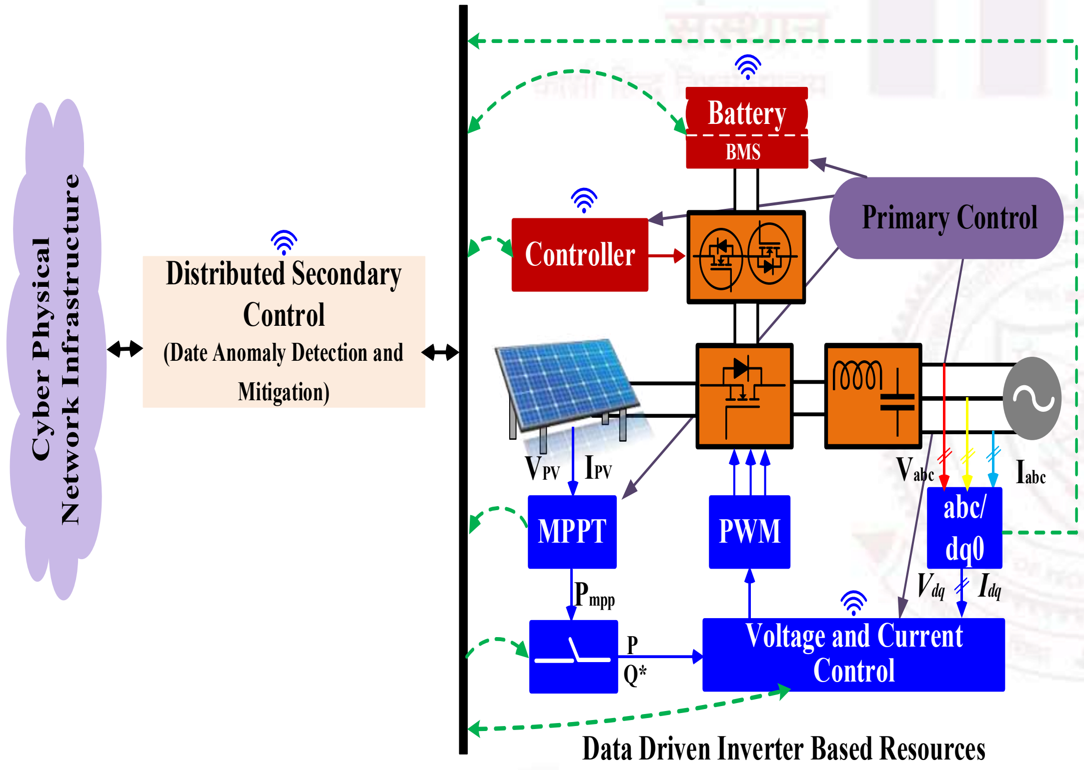

Flowchart for cyber resilient IBRs

- IBRs unit comprise various ***distributed generation sources***, including multiple solar units, battery, the grid, power electronic interfaces, and sensors.

- ***Collect, stream, and store data*** from inverter-based resources on the cloud, using AI algorithms to detect anomalies and ensure reliable secondary control.

- Secondary control defines reference signals for primary control to regulate the switching of power electronics interfaces, with ***human-in-the-loop integration*** enhancing the ***resilience and accuracy of IBR*** operations.

# Data Driven Inverter Based Resources (IBR) System




**Data driven converter- inverter system**

## Role of IBRs in Distributed Generation (DG).

- **Primary control :**
  Direct power electronic device control.
- **Secondary control:**
  Uses data processing of DGs of the grid and decides reference for primary control.

Above control schemes rely on communication networks using data sensors.

✓ Data collection along with anomaly detection and mitigation is the key.

X It makes the system vulnerable to cyber anomalies.

**Consortium Partners:**

Massachusetts Institute of Technology
WestVirginiaUniversity

***Reference:*** P. S. Sarker, M. F. Rafy, A. K. Srivastava and **R. K. Singh**, "Cyber Anomaly-Aware Distributed Voltage Control With Active Power Curtailment and DERs," in *IEEE Transactions on Industry Applications*, vol. 60, no. 1, pp. 1622-1633, Jan.-Feb. 2024, doi: 10.1109/TIA.2023.3328850.

# Data Driven Inverter Based Resources (IBR) System

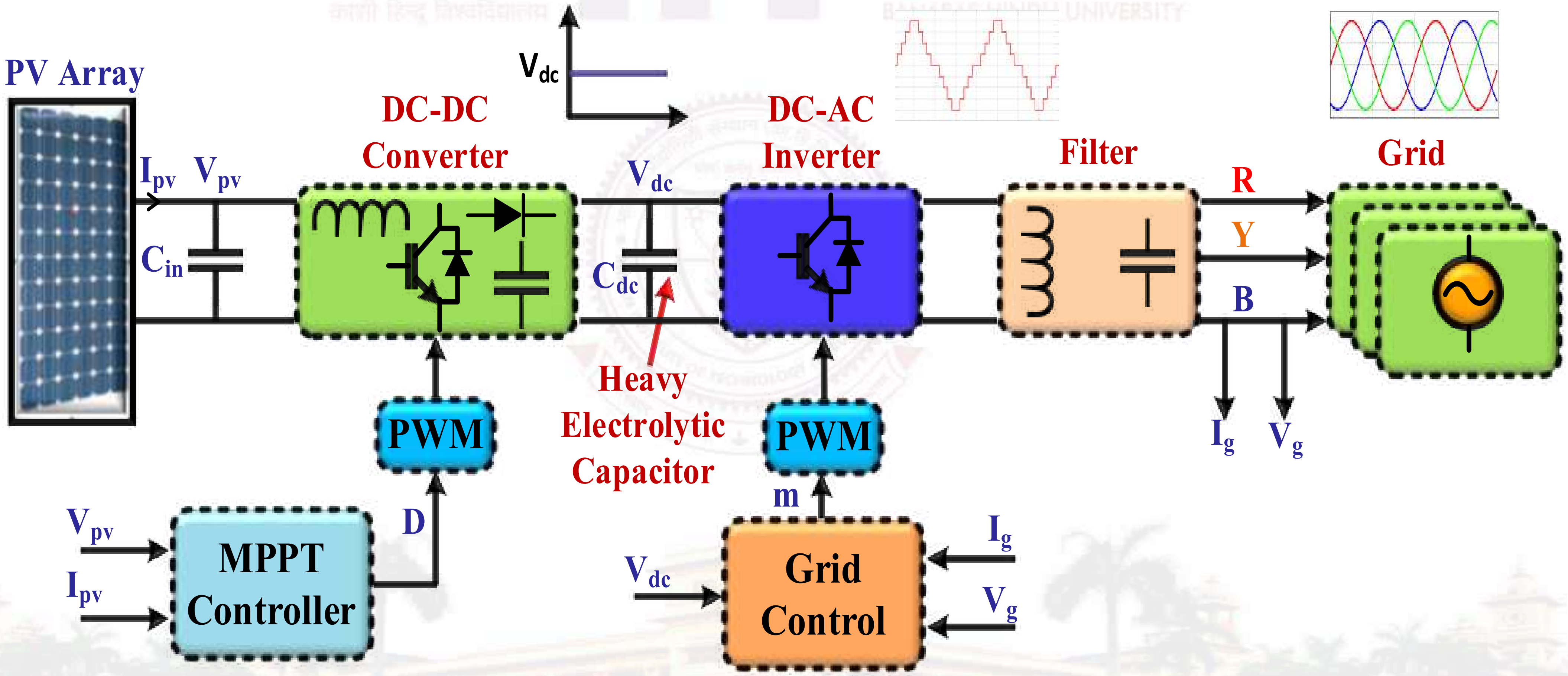
- Development of model of distributed system integrated inverter-based resources.
- Integration of battery in the IBRs with the PV system

- Development of scheme for data communication through cyber-physical networked infrastructures (CPNI).
- Design of prototype algorithms for data anomaly detection and mitigation.

- Design and development of adaptive distributed control algorithms for secure integration of DERs including IBRs embedded in an IOT network.

***Reference:*** P. S. Sarker, M. F. Rafy, A. K. Srivastava and **R. K. Singh**, "Cyber Anomaly-Aware Distributed Voltage Control With Active Power Curtailment and DERs," in *IEEE Transactions on Industry Applications*, vol. 60, no. 1, pp. 1622-1633, Jan.-Feb. 2024, doi: 10.1109/TIA.2023.3328850.

# Conventional Solar to Grid Connected System




Conventional solar to grid-connected system

## Problem Identification in Conventional Topology

- Conventional system uses electrolytic capacitor having lesser lifespan, high ESR value and less reliable.
- This may lead to the total failure of the entire system.

**Power flow Optimization (battery and grid)** ✗

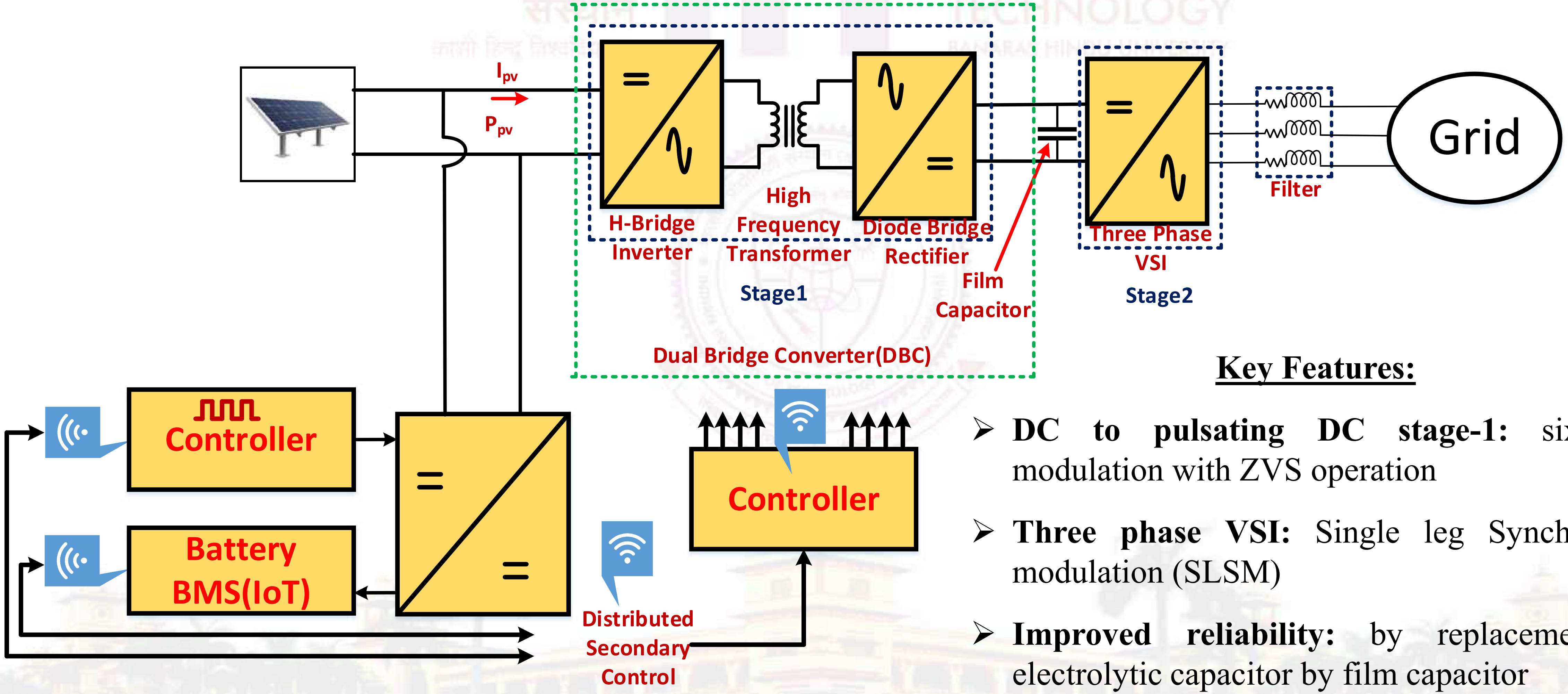
**Data driven predictive control** ✗

## Proposed Solution

- Heavy electrolytic capacitor DC link replaced by a small film capacitor.
- Inherent soft-switching- reduced switching loss
- Data driven predictive control for data anomaly detection and mitigation


| Electrolytic Capacitor | Film-Capacitor |
|---|---|
| Poor Life – span. | Improved Life – 10-15 years |
| Reliability is poor | Better reliability |
| Continuous monitoring is required -maintenance cost high. | Low maintenance cost |
| Protection system required | No protection system is required |

# Electrolytic Capacitor-less Proposed PV System Topology

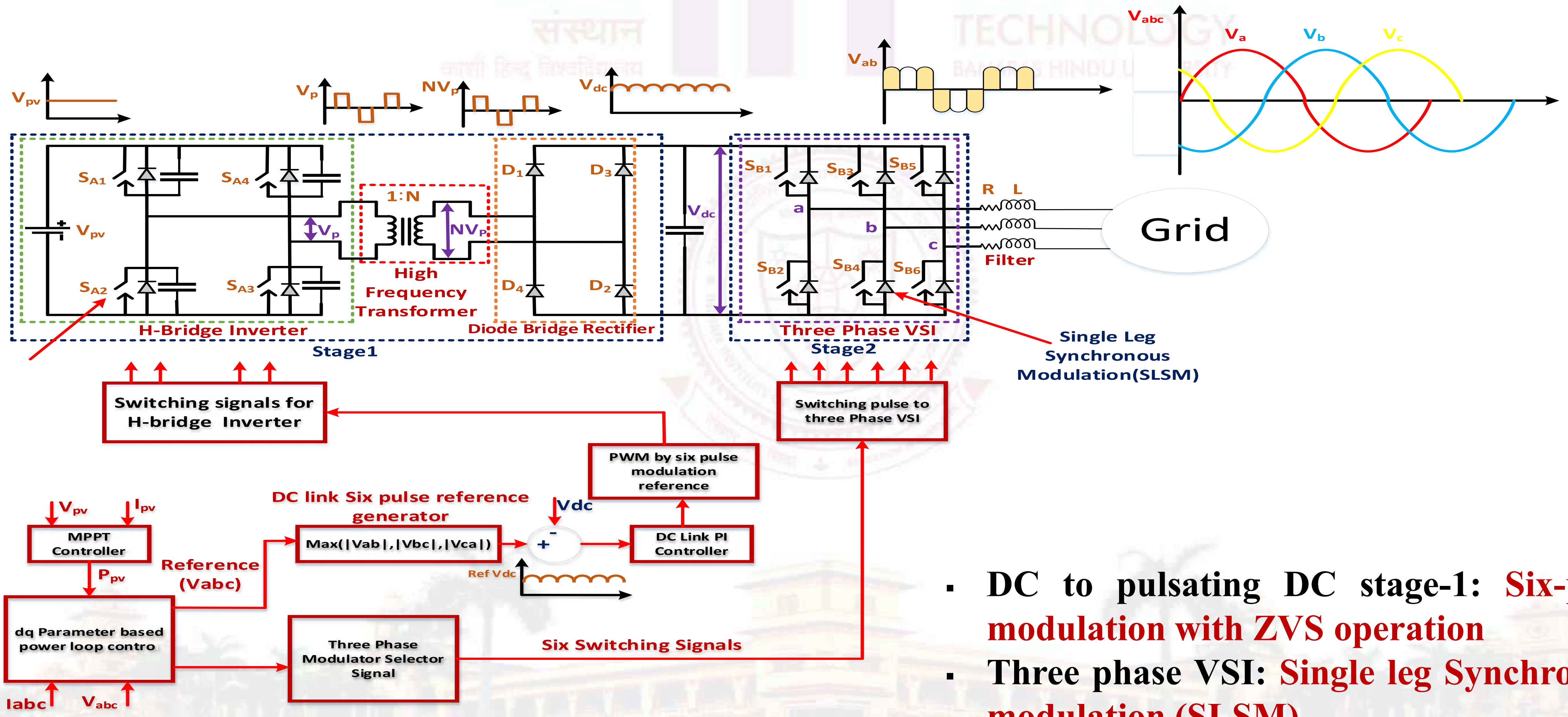



Block diagram of PV-based electrolytic capacitor-less converter

## Key Features:

- **DC to pulsating DC stage-1:** six-pulse modulation with ZVS operation
- **Three phase VSI:** Single leg Synchronous modulation (SLSM)
- **Improved reliability:** by replacement of electrolytic capacitor by film capacitor
- **IoT enabled monitoring and control.**

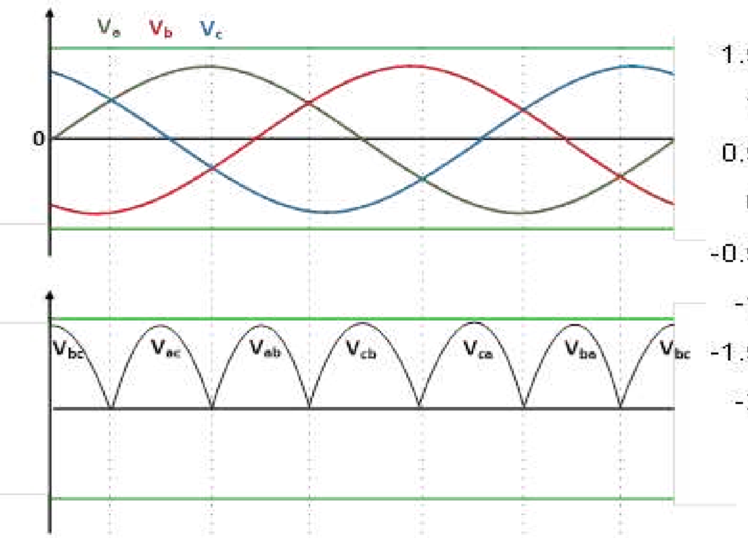
# Control Schemes for Proposed System

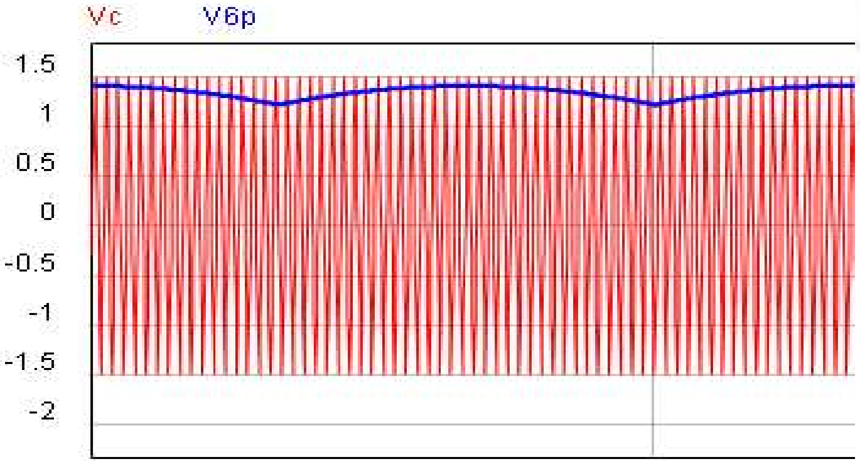


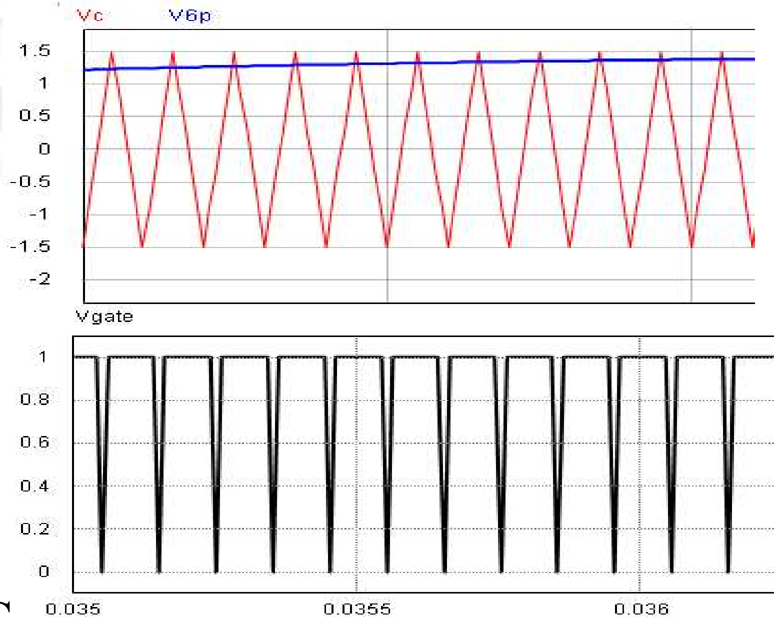

Control scheme for proposed system

- DC to pulsating DC stage-1: **Six-pulse modulation with ZVS operation**
- Three phase VSI: **Single leg Synchronous modulation (SLSM)**

# Modulation Techniques



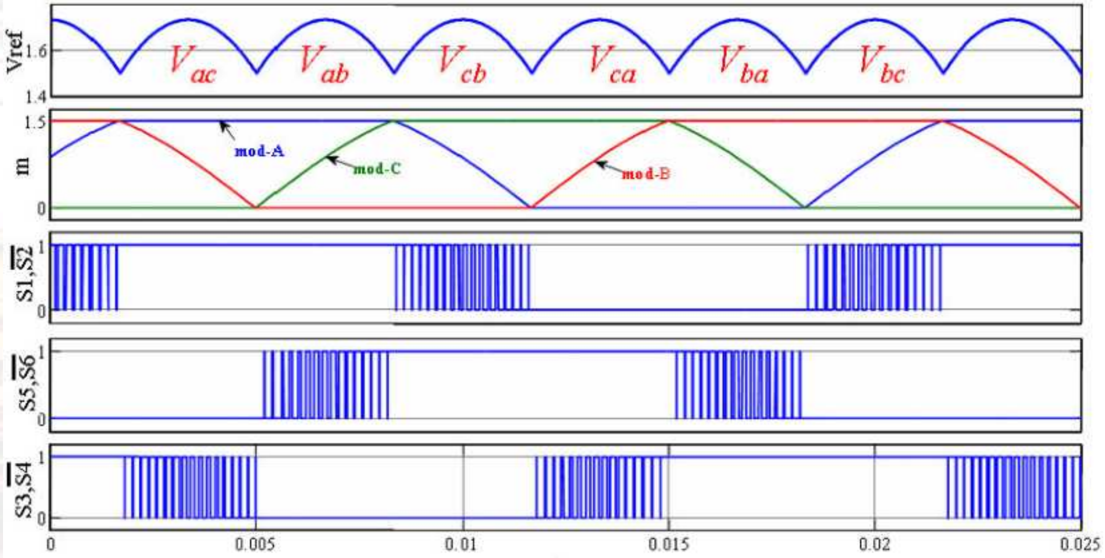




**Six pulse modulation scheme of DBC**

| Switch | T1 | T2 | T3 | T4 | T5 | T6 |
|---|---|---|---|---|---|---|
| S1 Ŝ2 | $\frac{V_{ab}}{V_{cb}}$ | 1 | 1 | $\frac{V_{ac}}{V_{bc}}$ | 0 | 0 |
| S3 Ŝ4 | 0 | 0 | $\frac{V_{bc}}{V_{ac}}$ | 1 | 1 | $\frac{V_{ba}}{V_{ca}}$ |
| S5 Ŝ 6 | 1 | $\frac{V_{cb}}{V_{ab}}$ | 0 | 0 | $\frac{V_{ca}}{V_{ba}}$ | 1 |

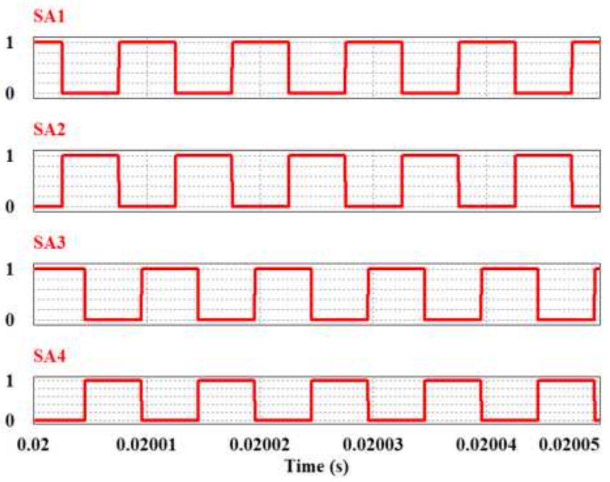
**Table: Switching scheme of 3- Φ Inverter**



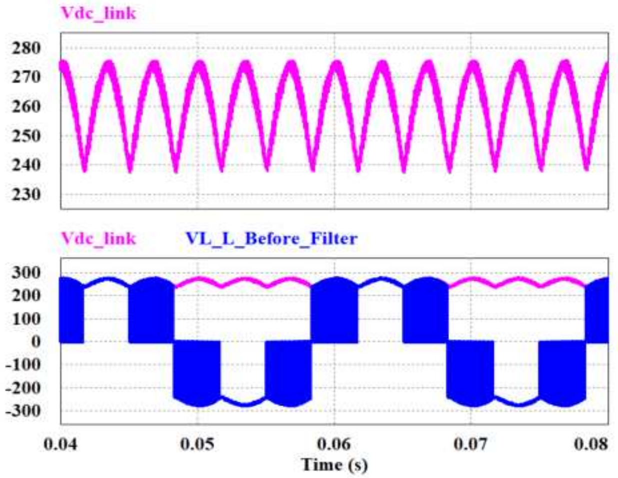

**Single leg synchronous modulation (SLSM) Three-phase inverter**

# Simulation Results of the Proposed Topology

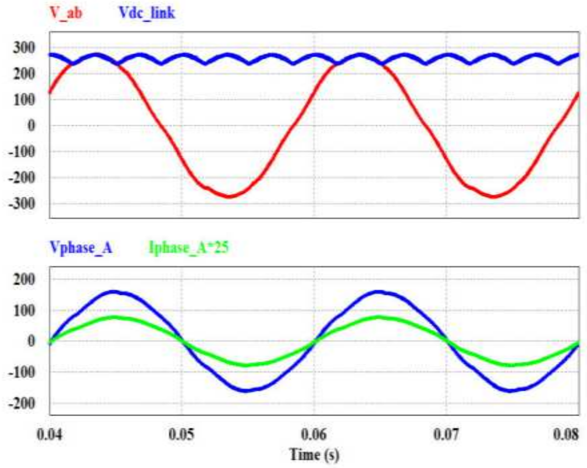
| System Specifications | Values |
|---|---|
| Output Power | 700 W |
| Output phase voltage | 110V (rms) |
| Load Resistance per phase | 52 Ohm |
| Output phase Current | 2.1 A (rms) |
| DC Link Voltage | 265 V |
| Transformer’s Turn Ratio (n) | 1:4 |
| Leakage inductance of HF transformer | 40 µH |
| Film capacitance | 5 µF |



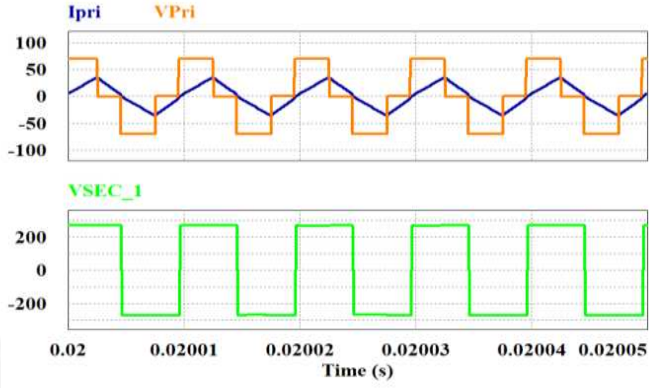

Gating Pulses to front end H-bridge inverter



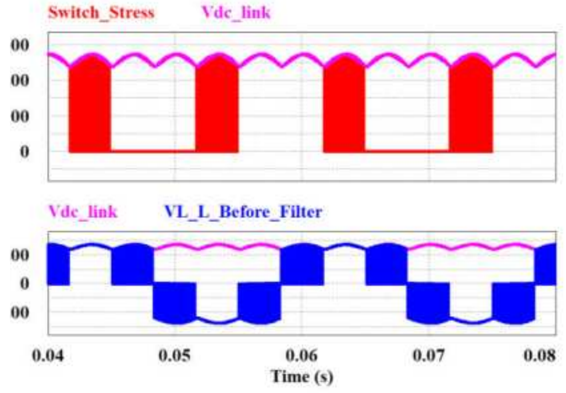

Voltage across DC link (Vdc_link) and Line to Line voltage before output filter



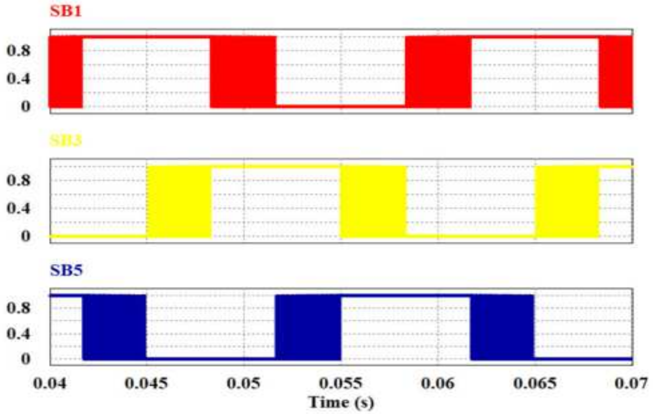

DC link voltage, line to line output voltage, phase output voltage and output phase current (25 times scaled)



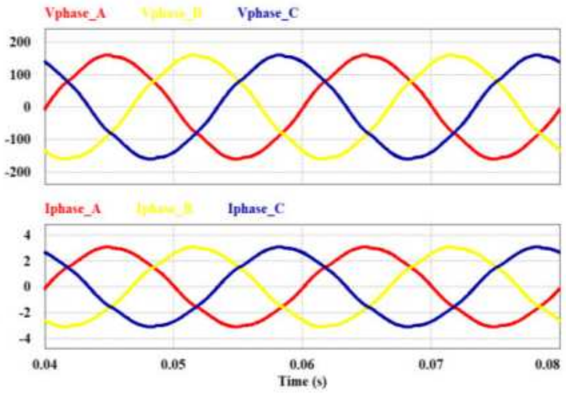

Primary voltage (Vpri) , primary current (Ipri) and Secondary voltage (Vsec) of High frequency transformer




Voltage across DC link (Vdc_link), Switch stress across back end inverter and Line to Line voltage without output filter

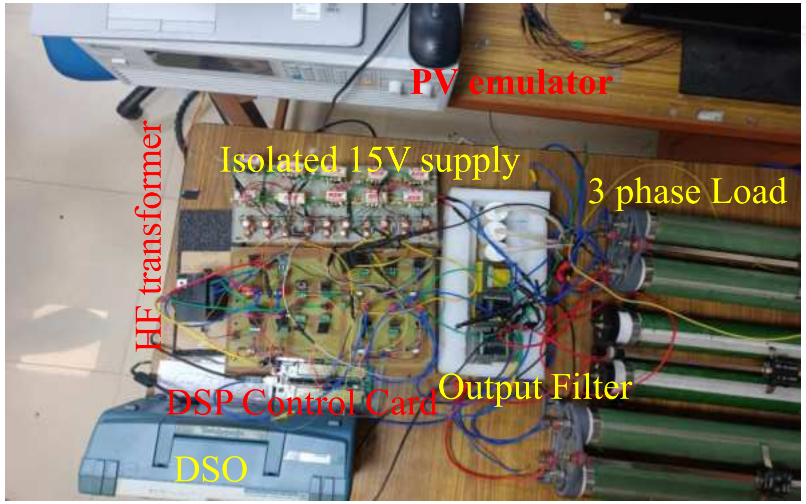



Gating Pulse for back end 3 phase inverter with SLSM technique

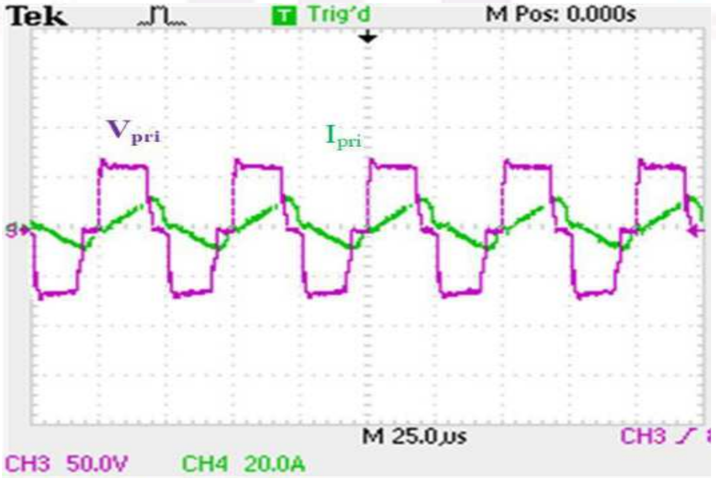



3 phase Output voltages and 3 phase output current

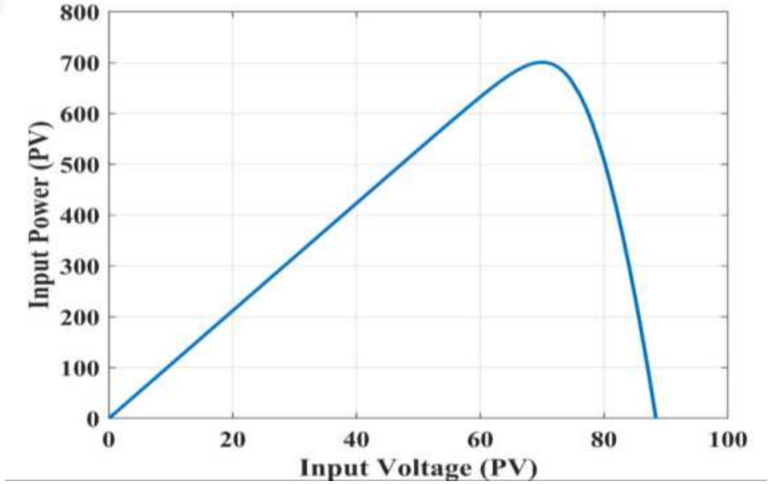
# Experimental Verification of Proposed Topology



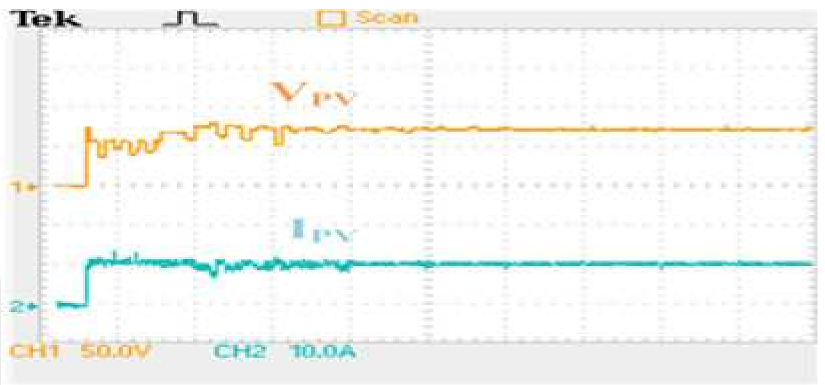

Laboratory prototype of proposed topology



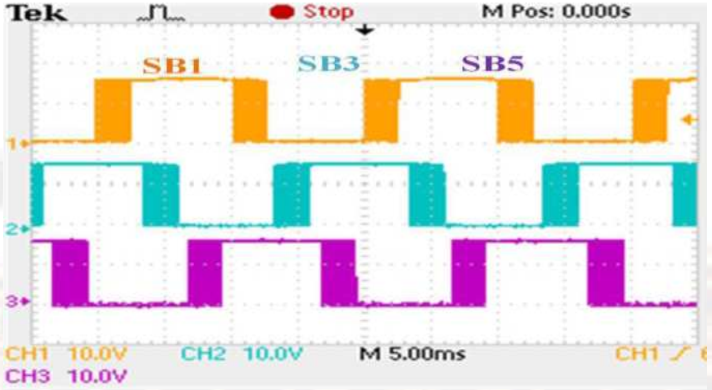

Primary voltage and Primary current of high frequency transformer



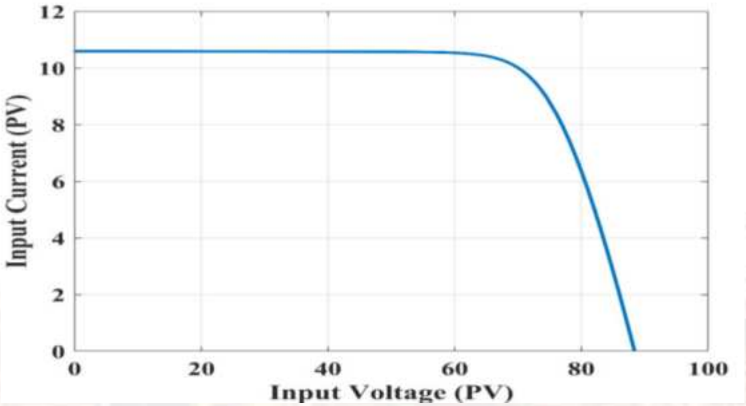

Curve between input power v/s input voltage




PV input voltage and current

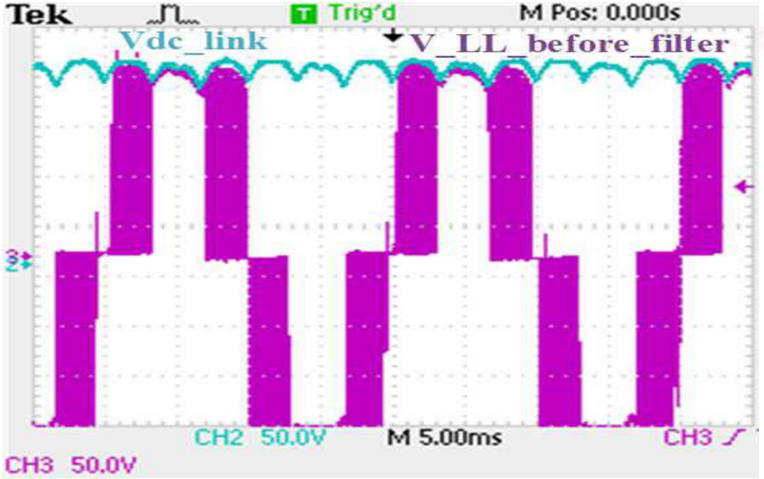



Gating Pulse for back end 3 phase inverter with SLSM technique



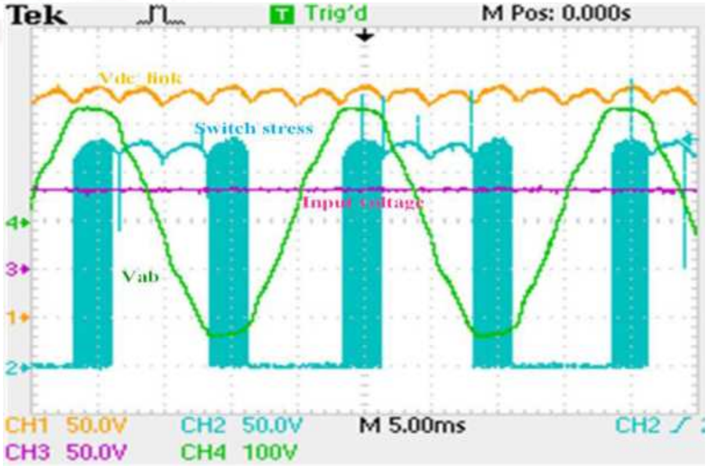

Curve between input current v/s input voltage

# Experimental Verification Contd…

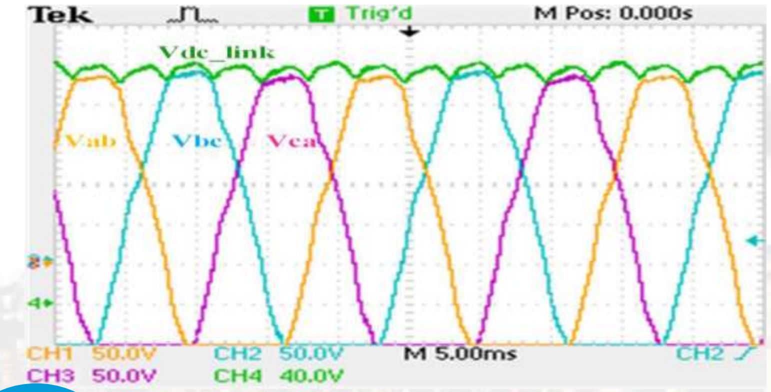



Voltage across DC link and line to line output voltage before filter

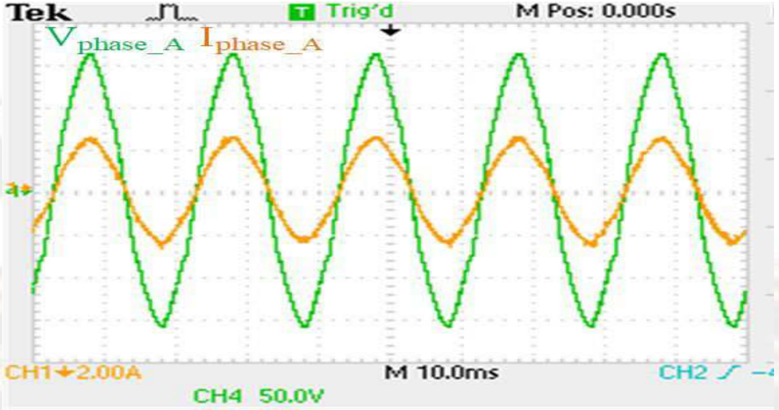

DC link voltage, Switch stress across back end inverter and input voltage



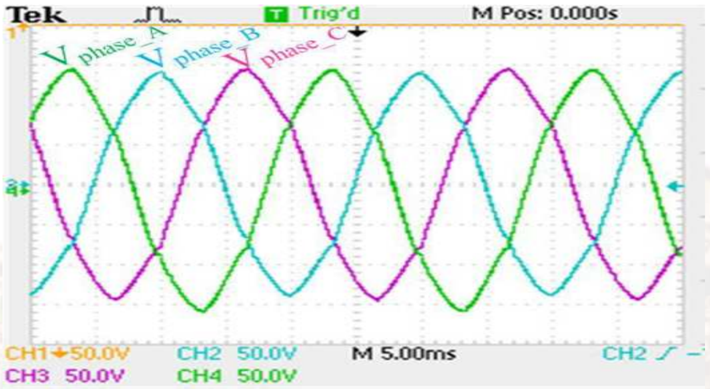

Voltage across DC link, switch stress across back end inverter and line to line output voltage




Voltage across DC link and three phase line to line voltages




Output phase voltage and output phase current



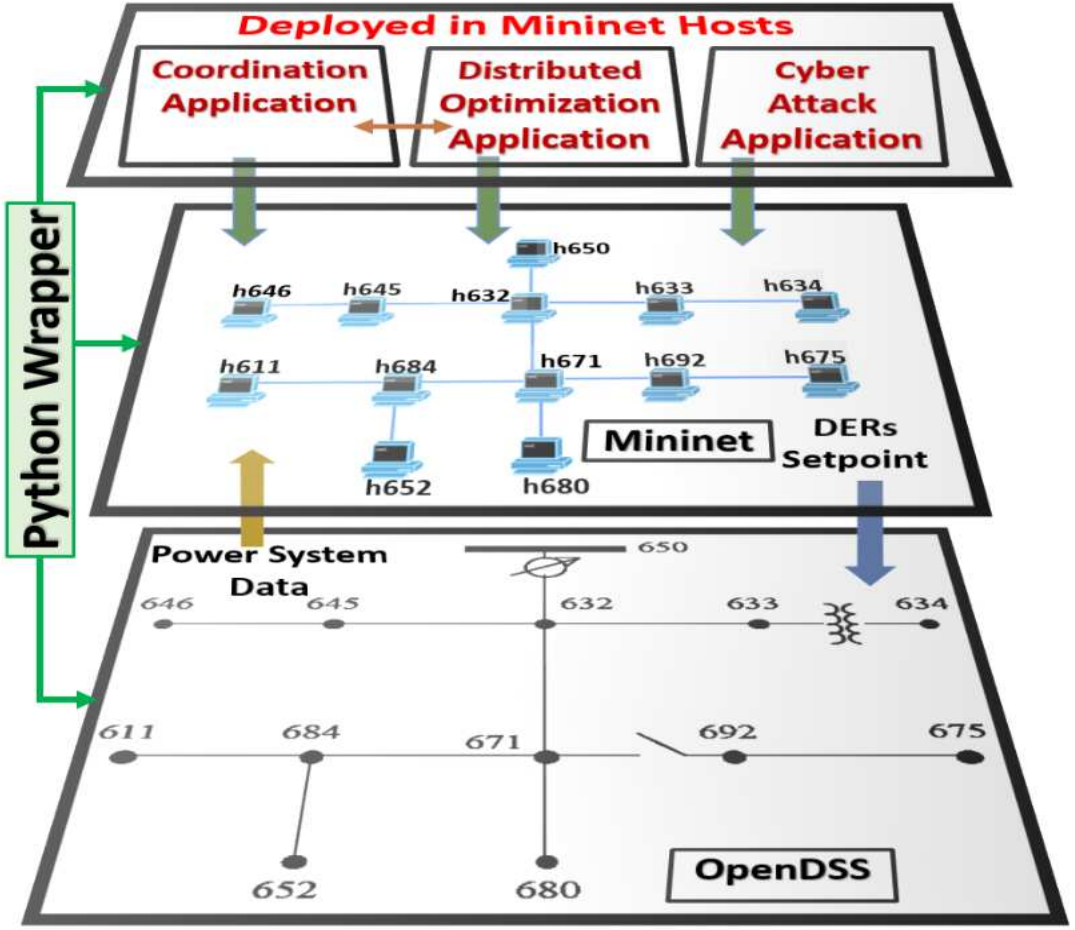

3 phase output voltages

# Cyber-Power Test-bed

- Power System Layer : Developed with OpenDSS
- Cyber Layer: Developed with Mininet
- Application Layer : Developed with Python
- Python Wrappers binds all three layers

Challenges:

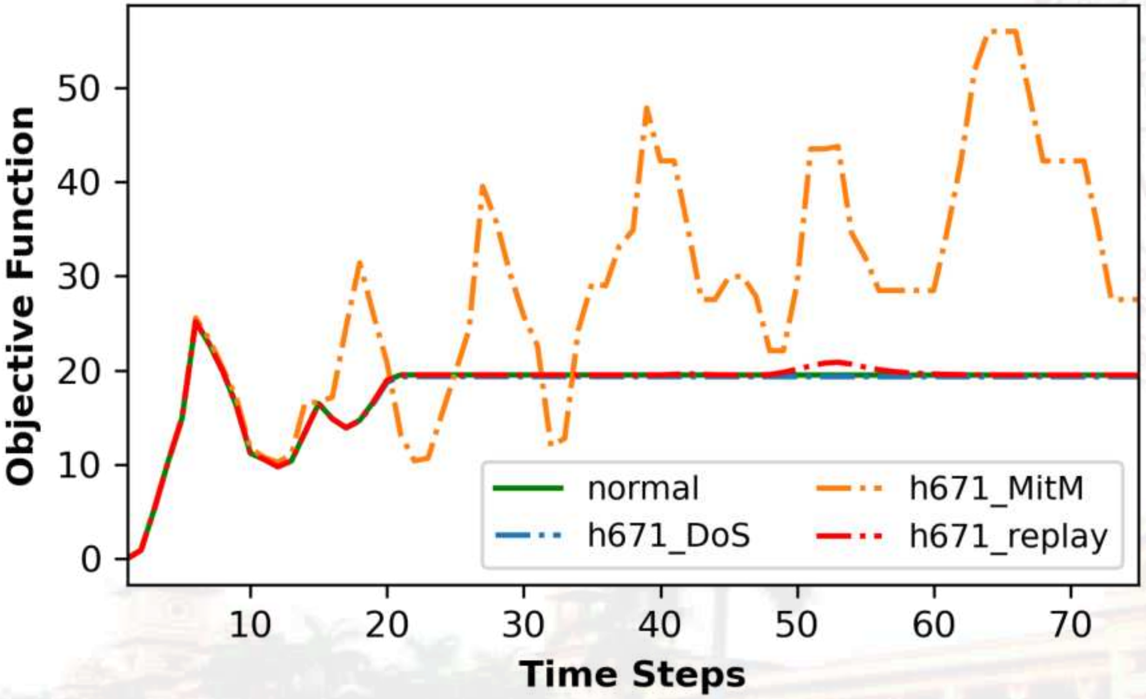
- Data flow among layers
- Time synchronization
- Running applications in Mininet hosts
- Facilitate Plug-&-Play Capability

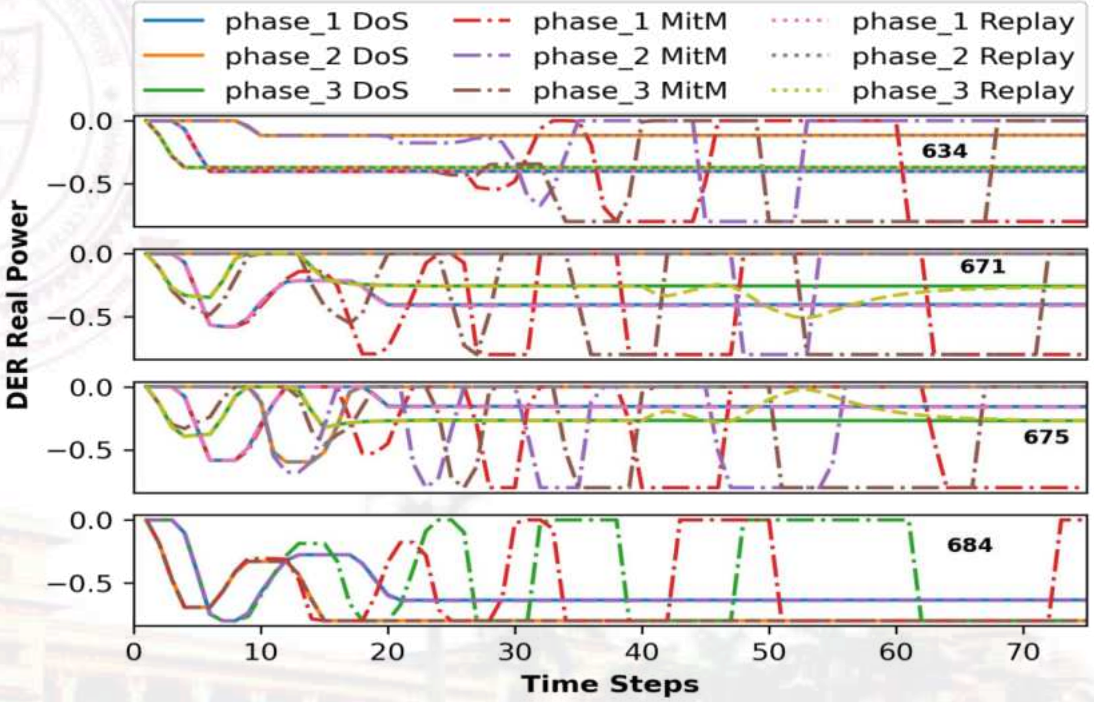



Smart grid system with communication network

# Test Cases & Results

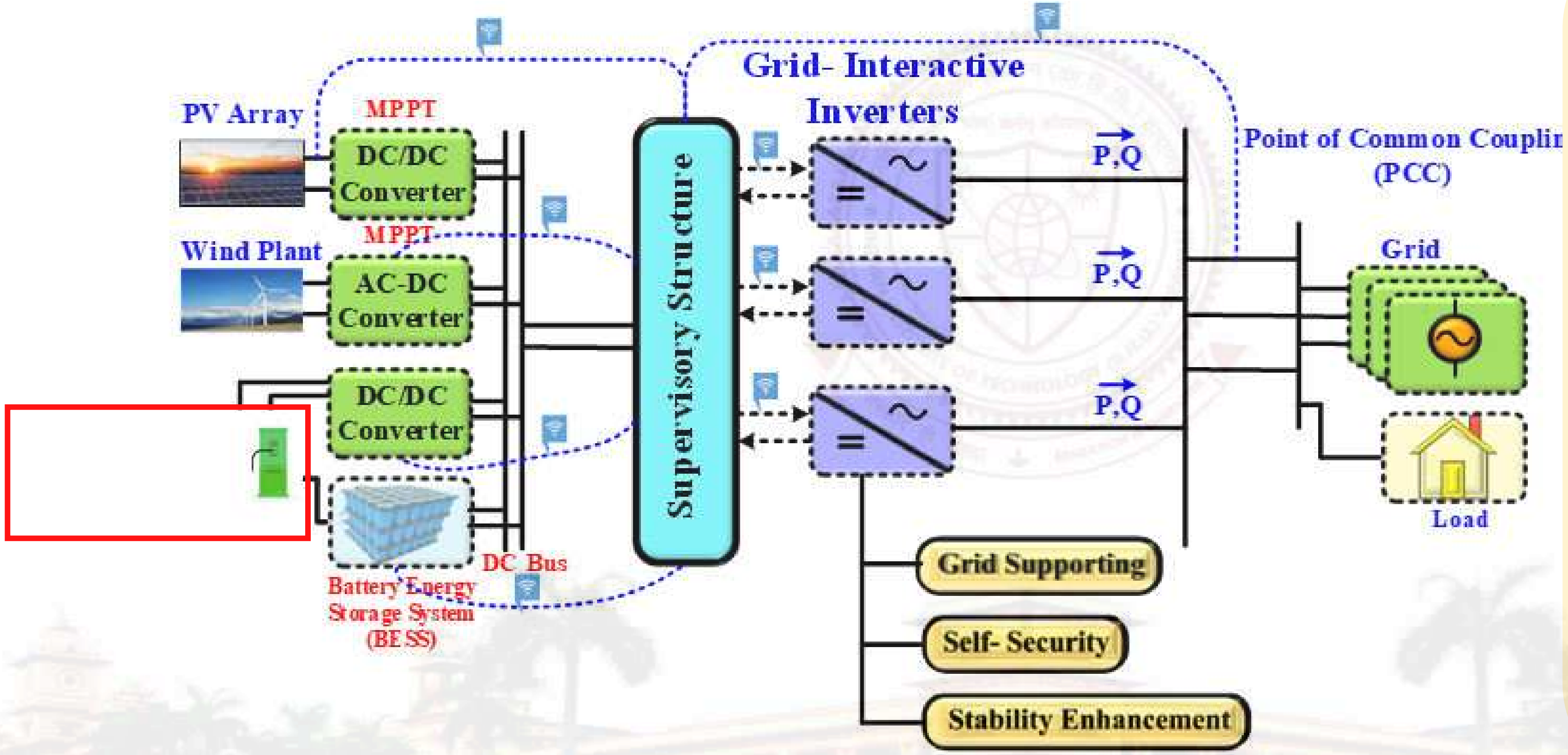
- Use case:
  - DERs are connected at nodes 671, 684, 675, and 634.
  - h634 and h671 are under attack with MitM, DoS, and Replay individually.



# Cyber-Resilient Smart Grid Systems: The EV Perspective

# Role of EV in Smart Grid Architecture




EV-Integrated Smart Grid Architecture

## Key Features

- **EV as a load**
  - Home charging
  - Fast Charging
  - Ultra-fast charging
- **EV as a Source:**
  - V2G, V2H, V2V
  - Back-up power
  - Load smoothening
  - Grid balancing

# EV Charging Impact on Distribution Networks

## The Challenges

➢ **Power Quality Issues:**

- Harmonic distortions into the system, reducing power quality and causing overheating in transformers.
- Multiple EV chargers starting simultaneously can cause short-term voltage fluctuations (flicker).

➢ **Feeder Line Overloading:**

- Thermal stress on the feeder line leads to cable failure and insulation damage.
- Reducing the ability to supply power efficiently to other connected customers.


➢ **Peak Load Amplification:**

- Can amplify peak demand significantly, exacerbating the stress on the distribution network.
- Increased peak demand may push the grid infrastructure beyond its capacity, leading to congestion, and blackouts.

➢ **Voltage Fluctuations and Sags:**

- Heavy and uncoordinated charging in a neighborhood can cause significant voltage drops along the distribution feeders.
- Single-phase EV chargers connected disproportionately to one phase of the three-phase network, can cause voltage unbalance.

# EV Charging Impact on Distribution Networks

## The Solutions

**Voltage Unbalance Mitigation**

- Communication system enabling
- Charging coordination between EV and the aggregator
- Collects and transmits data
- Standardize the voltage profile

**Harmonic Mitigation**

Ensure Unity power factor
Control of IBRs using advanced modulation techniques

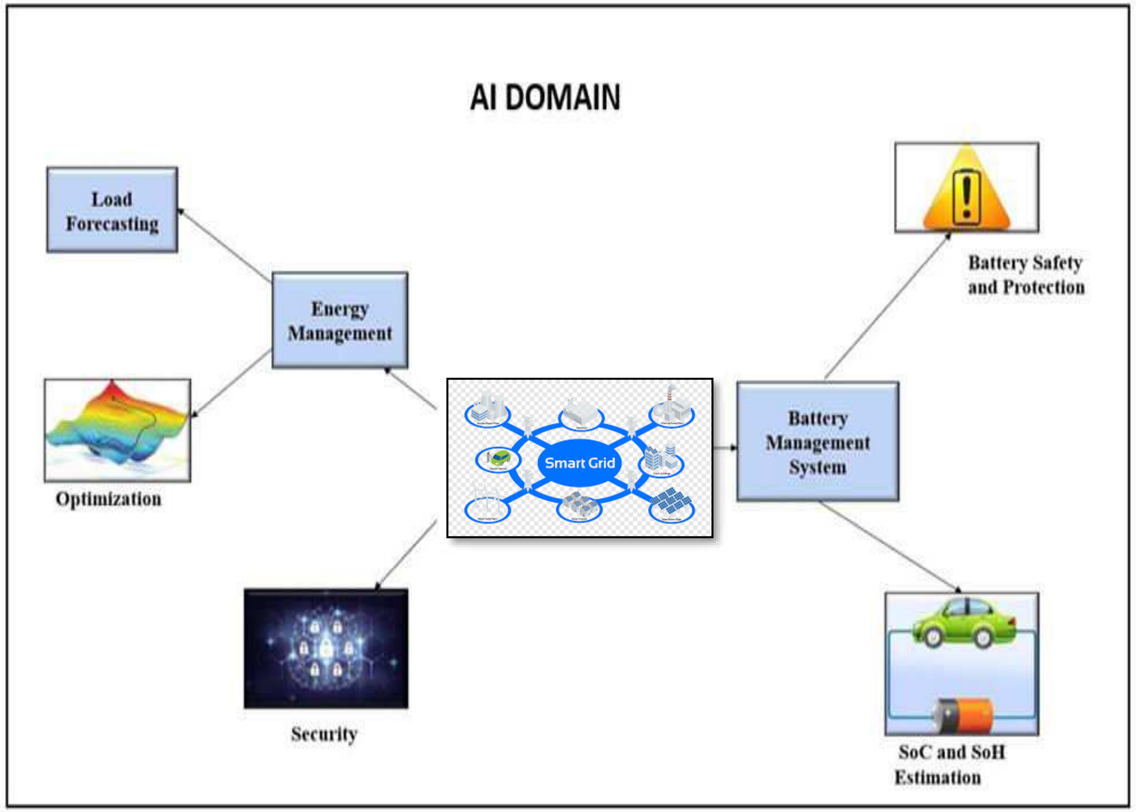
**Voltage Fluctuations**

Vehicle to grid communication support

## AI based Solutions

- Predictive Maintenance
- Intelligent Demand Response
- Optimizing Battery Performance.
- Dynamic Energy Management
- Enhanced Grid Stability
- Efficient Resource Utilization

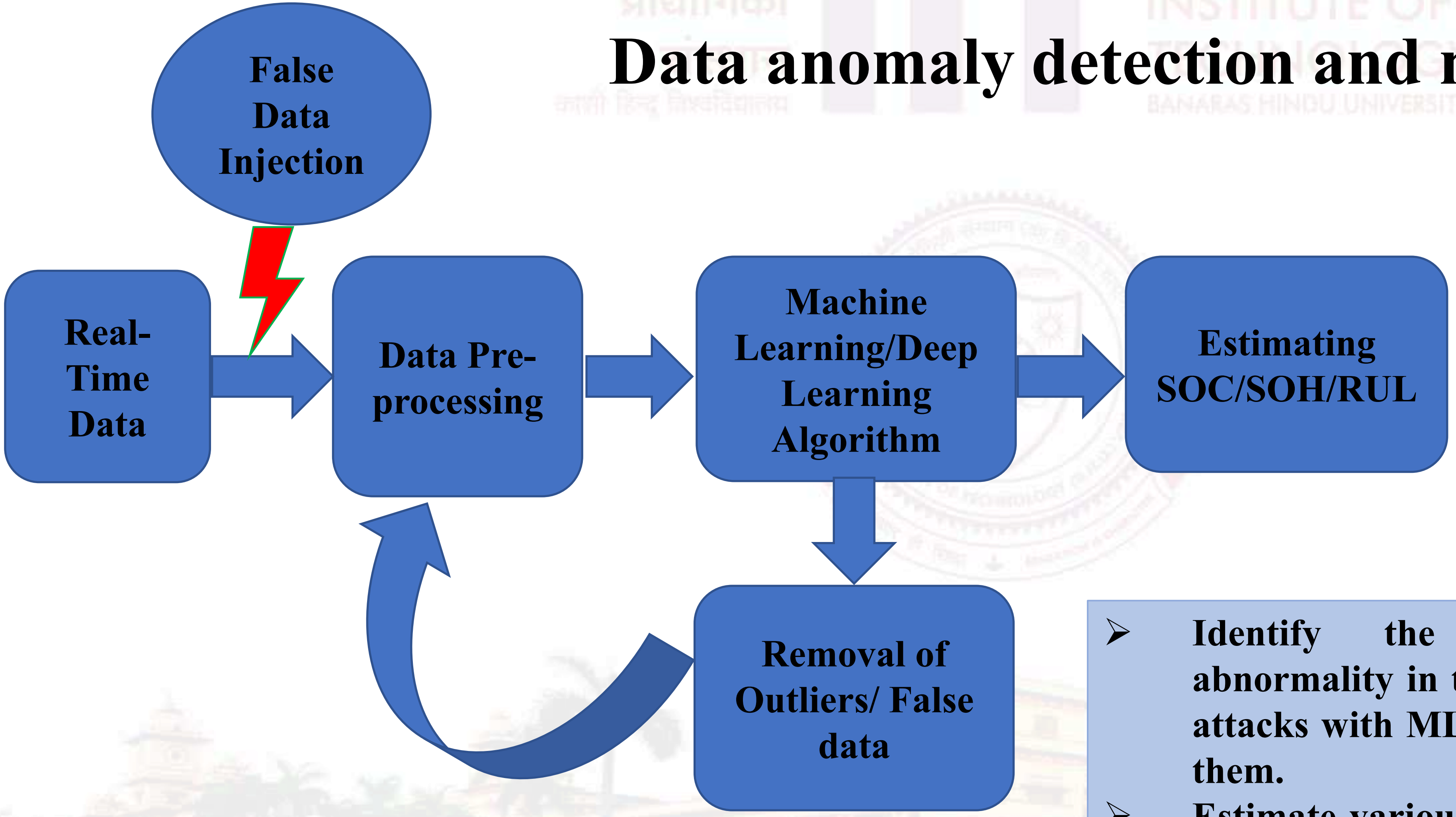
# Role of AI in EV Integration to smart grid




Application of AI in Smart Grid

- **Data anomaly detection and mitigation.**
- **Predication of power generation by DERs.**
- **Load forecasting.**
- **Power flow optimization**
- **Predication of SOC, SOH and RUL**

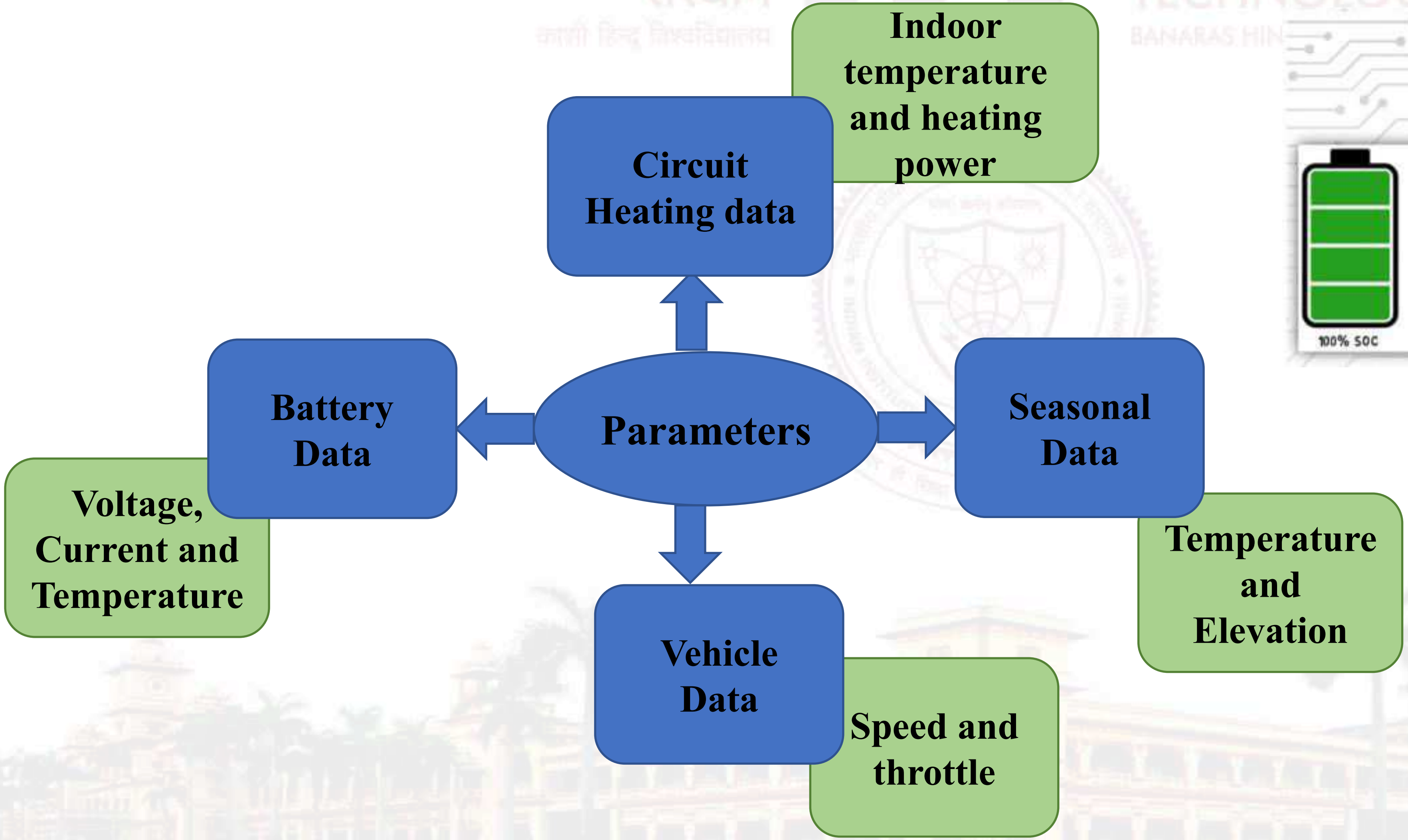
# Data anomaly detection and mitigation



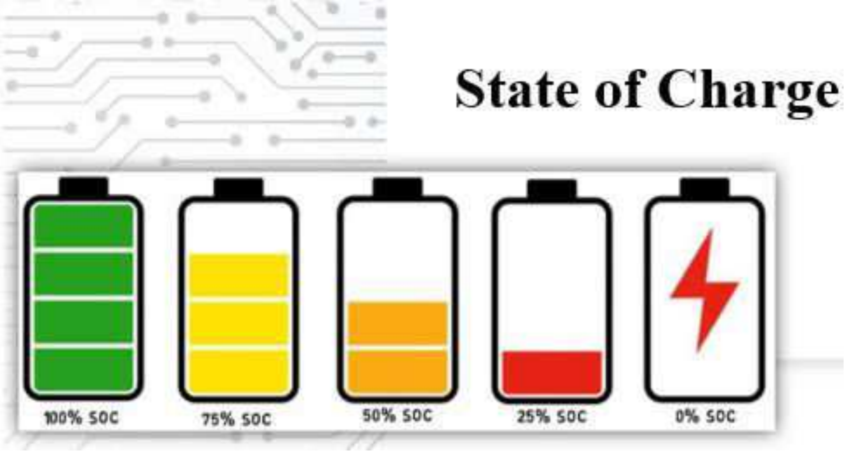

Block diagram showing data anomaly detection and mitigation

- Identify the equipment failures and abnormality in the real time data due to cyber-attacks with ML based algorithms and mitigate them.
- Estimate various battery parameters effectively by using efficient time series algorithms.

# State of Charge (SOC) Estimation




Parameters used for SOC estimation

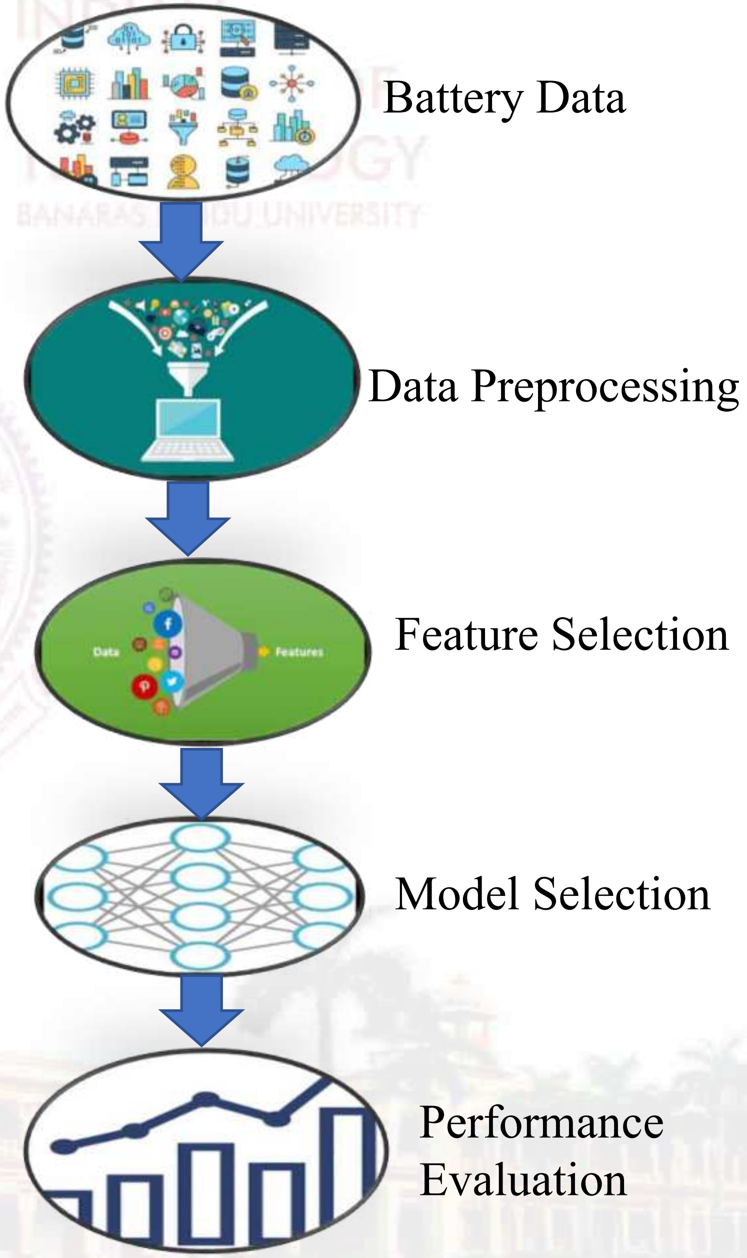



- SOC is the state of charge (percentage value), which gives an indication of the battery state during charge and discharge process as compared to its full-charge state.

# Workflow for SOC estimation:

**Steps involved in SOC estimation:**

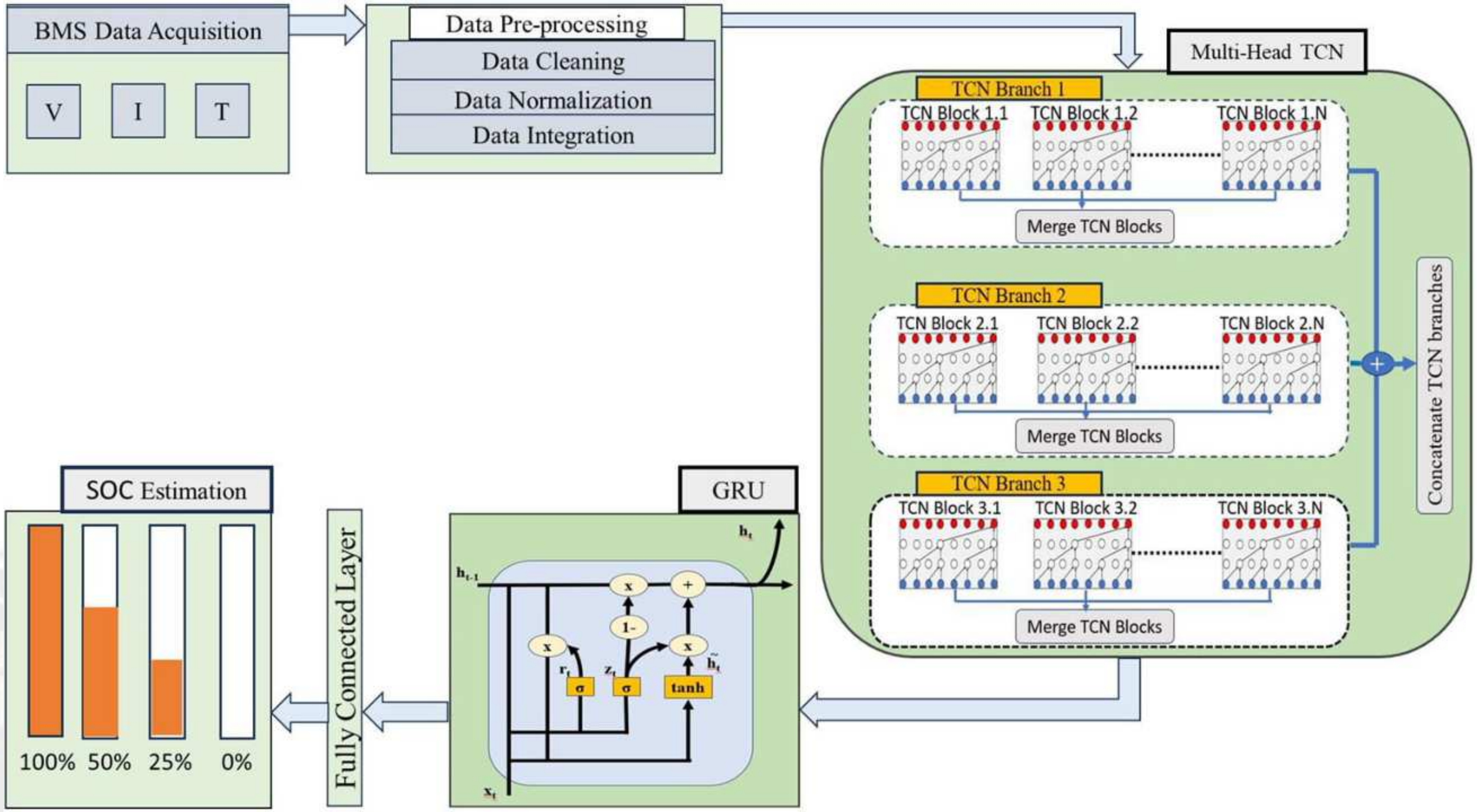
1. Start
2. Data Pre-processing:
   2.1 Combine all trips into one CSV file
   2.2 Remove NAN values
   2.3 Perform feature selection
3. Apply different deep learning algorithms:
   3.1 Select the first algorithm
   3.2 Train the model
   3.3 Evaluate the model using performance metrics
   3.4 Store the evaluation results
   3.5 Repeat steps 3.1-3.4 for each subsequent algorithm
4. Select the best model:
   4.1 Compare the evaluation results of each model
   4.2 Choose the model with the best performance
5. End




**Workflow for SOC estimation**

# Battery Life Prognosis

*A novel hybrid architecture combining Multi-Head Dilated TCN and GRU is proposed for SOC estimation.



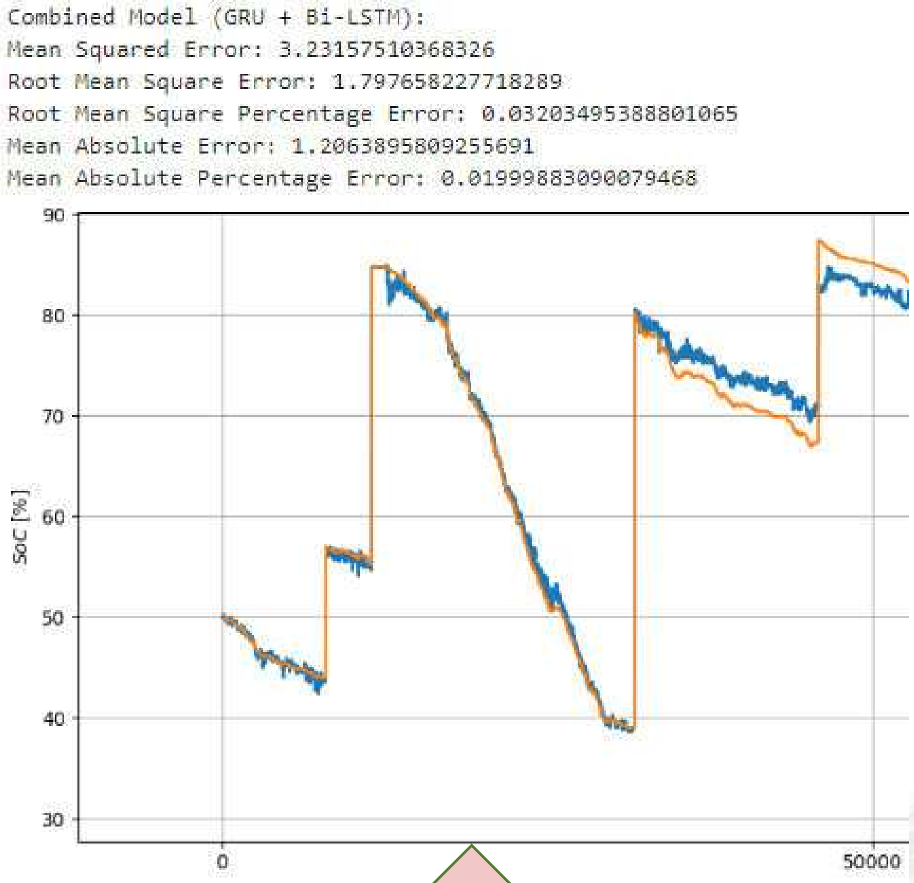
# Prediction of SOC using time series algorithm

## Battery and Heating Data in Real Driving Cycles

- 72 real driving trips with a BMW i3 (60 Ah)
  Each trip contains:
  - Environmental data (temperature, elevation, etc.)
  - Vehicle data (speed, throttle, etc.)
  - Battery data (voltage, current, temperature, SoC)
  - Heating circuit data (indoor temperature, heating power, et
- The measurement data is in CSV format.
- The measurement data is divided into two categories.

❖ **Category A** was recorded in summer and does not contai measured data due to trouble with the measurement syste

❖ **Category B** was recorded in winter and is consistent.




**Predicted SOC is closely following the measured SOC.**

# Battery Life Prognosis

## Table 1-SOC Estimation at different ambient temperatures-LG Dataset

| Methodology | Metrics | -10 degree Temperature | 0 Degree Temperature | 10 Degree Temperature | 25 Degree Temperature | Parameters |
|---|---|---|---|---|---|---|
| CNN+BWGRU [40] | MAE%<br>RMSE% | 0.81<br>1.13 | 0.44<br>0.53 | 0.79<br>1.06 | 0.49<br>0.54 | 555079 |
| Stacked-GRU [41] | MAE%<br>RMSE% | 4.12<br>5.32 | 2.39<br>2.96 | 1.88<br>2.47 | 1.37<br>1.93 | 23601 |
| iBiGRU-UKF [39] | MAE%<br>RMSE% | -<br>- | 0.83<br>1.12 | **0.67**<br>**0.74** | 0.52<br>0.61 | - |
| CNN+BiLSTM [26] | MAE%<br>RMSE% | 1.11<br>1.46 | 0.53<br>0.69 | 1.37<br>1.81 | 0.76<br>1.07 | 949521 |
| VMD+TCN [34] | MAE%<br>RMSE% | 6.60<br>9.49 | 4.94<br>7.20 | 6.50<br>8.51 | 7.15<br>10.25 | 57313 |
| **MHDTCN+GRU (Our Method)** | MAE%<br>RMSE% | **0.67**<br>**1.11** | **0.29**<br>**0.39** | 0.69<br>0.98 | **0.40**<br>**0.52** | 374433 |

## Table II- Estimation Under Varying Initial SOC Values

| Initial SOC | MAE | RMSE | Training Time |
|---|---|---|---|
| 100% | 0.0046 | 0.0072 | 2 hours 35 minutes 16 seconds |
| 80% | 0.0099 | 0.0122 | 2 hours 1 minute 47 seconds |
| 60% | 0.0098 | 0.0125 | 1 hour 25 minutes 36 seconds |

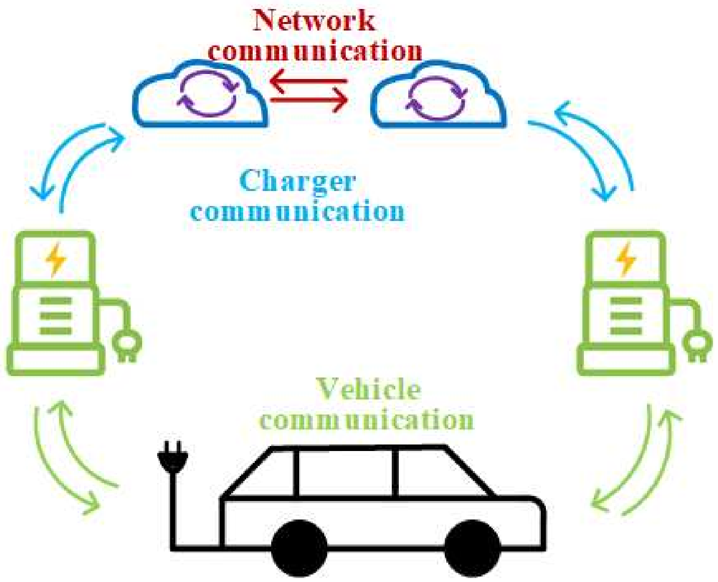
## Table III-SOC Estimation for different driving cycles of BMW I3

| Methodology | MAE (%) | RMSE (%) | Parameters |
|---|---|---|---|
| Stacked GRU | 0.0072 | 0.0086 | 16,705 |
| CNN-BiGRU | 0.0094 | 0.0124 | 13,985 |
| CNN-BiLSTM | 0.0086 | 0.0114 | 17,953 |
| TCN-GRUA | 0.0144 | 0.0159 | 28,770 |
| VMD-TCN | 0.0101 | 0.0127 | 17,281 |
| **MHDTCN-GRU** | **0.0049** | **0.0059** | **7,393** |

# CPS Network System and EV

## Need of Communication

- ➢ Establish proper connectivity.
- ➢ Charge duration, energy flow direction, availability of power and energy rate.
- ➢ Vehicle status information like SoC, useable battery energy
- ➢ To connect vehicle through IoT and smart charging station.




## EV Communications

### ➢ Vehicle to charger communication

- Vehicle to EVSE and vice-versa.
- **SOC of the battery.**
- Ensures proper battery **SOC** and safe operation of **grid**.

### ➢ Charger to network communication

- Data from the **EVSE to a network** through charger communication standards.
- Enables **smart charging operations**.

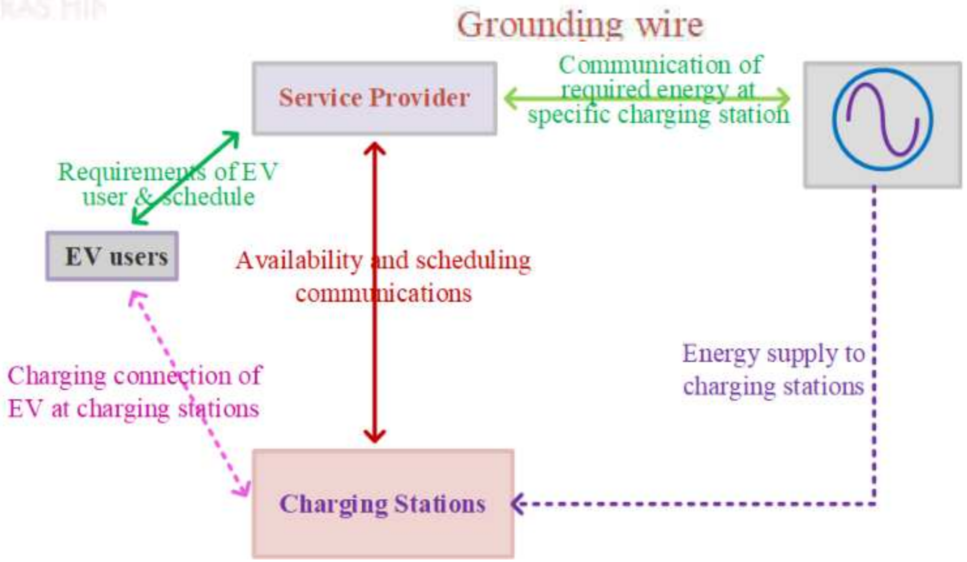
### ➢ Network to network communication

- Allows the flow of data throughout the third-party data provider.

# EV Communication Protocols

## *CAN Bus*

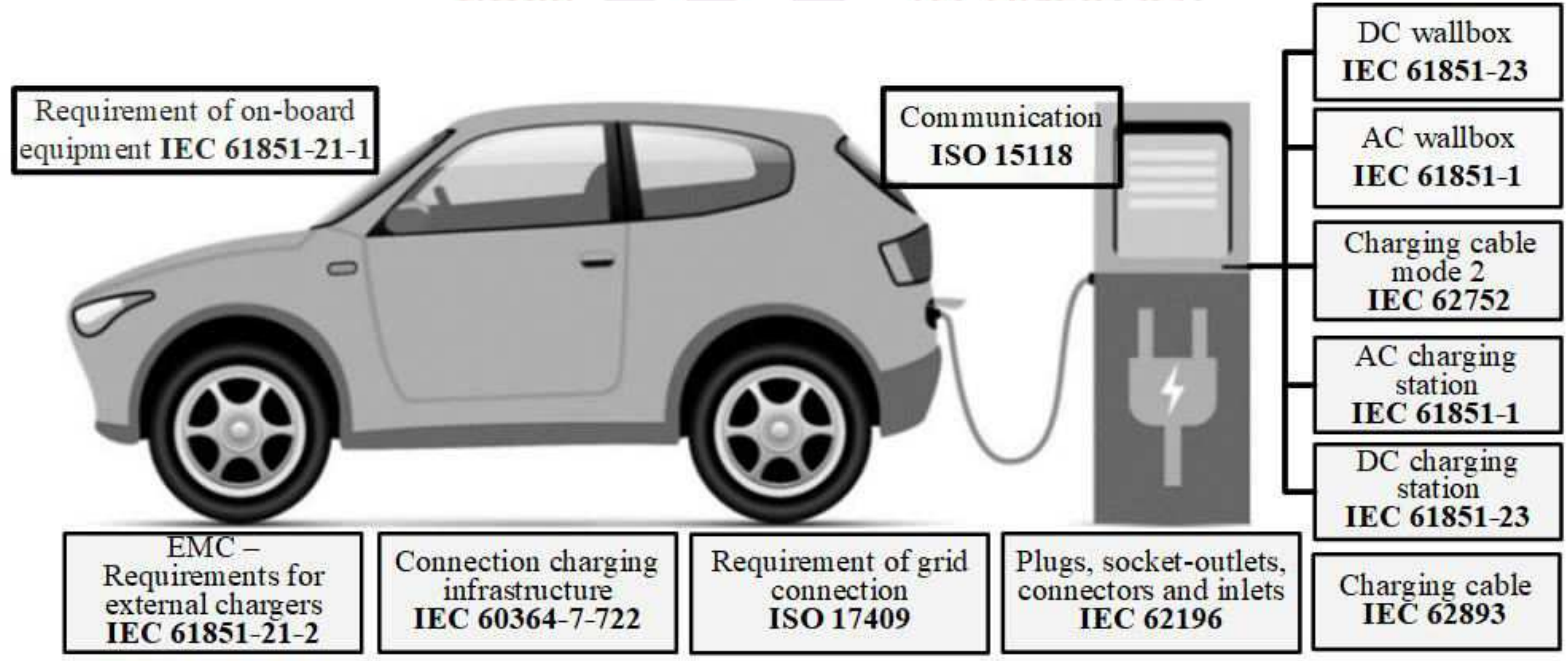
- **Controller Area Network (CAN)** is a vehicle communication protocol.
- Allows microcontrollers and devices to communicate without a host computer.
- Oversees the operation of **different devices** within the vehicle including the battery **SOC**.
- CAN Bus protocol is accessed through an **on-board diagnostics**.




## EVSE Communication Protocol

- **ISO 15118:**
  - Used for **road vehicle to grid** communication.
  - Ensures **safe delivery of energy** to the battery.
  - Enables **plug-and-charge capabilities** for streamlined transaction process in public charging.
- **OCPP (Open Charge Point Protocol):**
  - Enables communication between the **EVSE and host** network provider.
  - Enables **smart charge control.**

# Important EV Protocols




**Important protocols related to EV charging**

# Research Group Information

## Fundings :

| | Ongoing | Completed | Total |
|---|---|---|---|
| Total No. of Project | 6 | 7 | 13 |
| Total Budget Outlay | Rs. 7,62,90,942/- | Rs. 1,75, 90,407/- | Rs. 9,38,81,349/- |

**- Research Publications: 48 *Transactions/Journals + 88 Conferences***

**- Book Chapter: 2**

**- Patents Granted: 2**

**Group:**

**- Ph.d: 8 Graduated + 12 (On going)**

**- M.Tech: 56 (graduated) + 5 (ongoing)**

**- Post Doctoral Students: 2; JRF: 02; Technician: 03**

## Key Funding Agencies:

- Department of Science and Technology, Govt. of India
- Ministry of Electronics and Information Technology
- Central Power Research Institute
- IDAPT Hub Foundation
- Council of Science & Technology, Uttar Pradesh (UPCST)
- OEMs of Electric Vehicles Components

- For more details: Please visit @ https://iitbhu.ac.in/dept/eee/people/rksingheee

# Thank You

# Points for Discussion

- Smart Grid Ecosystem: Need, Contemporary And Futuristic Solutions
- Integration of Inverter-rich Cyber Physical System in Smart Grid Architecture
- EVs and the Cyber Resilient Smart Grid
- Protocols and Standards for EV Integration into Smart Grid