Format for uploading details of completed projects

1. **Project details**

   a. *Title*: Adaptive Control and Energy Management for Electric Vehicle Integrated Stand-alone Micro-Grid Operations.

   b. *Institute*: Institute of Engineering & Technology, Sitapur Road, Lucknow-226021, Uttar Pradesh

2. **Aim / Objectives:**

The following objectives were identified to be pursued and achieved within the scope of this project:

A. Exploration of a stand-alone microgrid system for voltage and frequency regulation through EV fleet control, without conventional power grid, while minimizing the requirement of large battery storage system.

B. Development of adaptive controllers for emulation of virtual inertia and damping in microgrid.

C. A unique Energy Management (EM) strategy for power flow maintenance as well as EV charging and discharging.

D. Real-time validation through Controller Hardware-in-the-loop (C-HIL) testing.

3. **Executive Summary (*One page*):**

The project titled **"Adaptive Control and Energy Management for Electric Vehicle Integrated Stand-alone Microgrid Operations"** focuses on the development of advanced control and energy management strategies for reliable and sustainable operation of standalone microgrids integrating renewable energy sources and electric vehicles (EVs). The study addresses key challenges associated with renewable-based islanded microgrids, including intermittent generation, limited energy storage, reduced system inertia, and fluctuating load demand. The primary objective of the project is to design an efficient microgrid architecture that ensures stable voltage and frequency regulation while minimizing the dependency on large stationary battery storage systems by utilizing EV batteries as flexible energy storage resources.

The work carried out in this project has been systematically divided into four phases covering system planning, control strategy development, energy management design, and real-time validation.

In **Phase I**, optimal sizing of the standalone microgrid components was performed considering renewable energy resources, load demand, and electric vehicle availability. A **Synergistic Swarm Optimization** approach was employed to minimize the total system cost while maintaining reliability through the Loss of Power Supply Probability (LPSP) index. The results demonstrate that the integration of EV storage through Vehicle-to-Grid (V2G) strategies significantly reduces the requirement of large battery storage systems while improving system reliability and energy efficiency.

In **Phase II**, a novel adaptive control strategy was developed for the grid-forming voltage source inverter used in the standalone microgrid. Unlike conventional control schemes that regulate the inverter filter capacitor voltage, the proposed approach directly controls the magnitude and angular frequency of the inverter's internal voltage while considering DC-link dynamics. A **Virtual Synchronous Generator (VSG)** based control framework was implemented to emulate the inertial behavior of conventional synchronous machines. To enhance dynamic performance, fuzzy logic rules were incorporated to adaptively adjust the virtual inertia and damping coefficients based on variations in system frequency and rate of change of frequency. Comparative analysis with conventional double-loop control schemes shows that the proposed strategy provides improved stability margins and robust voltage and frequency regulation under varying load conditions and renewable generation fluctuations.

Phase III focuses on the development of an advanced **Energy Management System (EMS)** for coordinated operation of renewable energy sources, EVs, and battery storage systems. Optimal charging and discharging schedules for a fleet of electric vehicles were generated using a day-ahead scheduling framework based on EV availability and energy requirements. A **Model Predictive Control (MPC)** based optimization module was implemented to update EV schedules in near real-time by incorporating the latest information related to renewable generation, load demand, and EV travel patterns. The updated schedules are communicated to the real-time energy management module at regular intervals, which generates appropriate control signals for EV charging modules and battery energy storage systems to maintain power balance and system stability.

In **Phase IV**, the developed control algorithms and energy management framework were validated through **Controller Hardware-in-the-Loop (CHIL)** testing to ensure their practical feasibility. The real-time testing environment integrates an **OPAL-RT OP4512 real-time simulator** with a **TI C2000-based TMS320F28379D microcontroller**, allowing real-time interaction between the controller hardware and the simulated microgrid model. The results confirm that the proposed control and energy management strategies are implementable in practical microgrid systems and maintain stable operation under dynamic operating conditions.

Overall, the project contributes significantly to the advancement of standalone microgrid technology by addressing critical aspects such as optimal system sizing, adaptive inverter control, and intelligent energy management. In addition to the technical contributions reported through journal publications (e.g., *IEEE Transactions on Industry Applications*, *Journal of Energy Storage*) and reputed international conferences, the project also facilitated knowledge dissemination through workshops and training programs focused on real-time simulation and hardware-in-the-loop testing for microgrid applications. A major component of the project was the acquisition of a real-time simulator, namely OPAL-RT, which was employed for the validation of the proposed strategies. Apart from the core research team, a number of undergraduate students and graduate students were trained to utilize the real-time simulation facility for their projects/thesis.

4. Scope for further work

The scope of this work can be further extended by validation of the proposed methodology through industry grade real-time simulators so that the control algorithms can be implemented with precise time and reliability.

Artificial Intelligence/Machine Learning based algorithms can be explored for more effective real-time energy management systems. Uncertainty modelling can be incorporated to take into consideration the variability of renewable generation and EV travelling patterns. Development of accurate digital twin models for the proposed structure is highly needed task for better system modelling, control strategies, fault detection etc.

Development of efficient EV scheduling algorithms that prioritize battery health and also provide ample flexibility to the EV owners while ensuring grid stability. Energy trading frameworks can be explored where EV owners can participate in energy markets within microgrids.

5. Benefits visualized

The benefits visualized from the project are summarized as follows:

Technical Benefits:

- Improved voltage and frequency regulation in standalone microgrids.
- Virtual inertia support using adaptive Virtual Synchronous Generator (VSG) control.
- Enhanced stability and dynamic response of low-inertia inverter-based systems.
- Reliable operation during renewable generation variability and load changes.
- Robust control performance under different load conditions.

Economic Benefits:

- Reduced requirement of large battery energy storage systems (BESS).
- Lower installation and operational costs due to utilization of EV batteries.
- Efficient utilization of available energy resources.
- Cost savings through optimized energy management and scheduling.
- Reduced dependency on expensive stationary storage solutions.

Environmental Benefits:

- Increased utilization of renewable energy sources such as solar and wind.
- Reduction in greenhouse gas emissions.
- Promotion of clean and sustainable energy systems.
- Support for green transportation through EV integration.

Operational and System Benefits:

- Electric vehicles operate as flexible energy storage through V2G and G2V modes.
- Improved reliability of electricity supply in remote or off-grid areas.
- Efficient real-time energy management and power flow coordination.
- Better load balancing and reduced power fluctuations.
- Hardware-in-the-Loop validation ensures practical feasibility and real-time implementation.