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# DYNAMIC PERFORMANCE ENHANCEMENT OF A HYBRID AC/DC PV–WIND MICROGRID THROUGH COORDINATED SUPERCAPACITOR-BASED CONTROL

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***Abstract.*** *This study presents a hybrid AC/DC microgrid designed to reduce unnecessary power conversions between alternating current and direct current systems. The AC and DC networks are interconnected using bidirectional converters, allowing power to flow efficiently between them and reducing conversion losses. The proposed hybrid microgrid operates in two modes: grid-connected and autonomous. Renewable energy sources, loads, and energy storage devices are connected on both AC and DC sides based on their natural operating characteristics. The system is modeled and simulated using the MATLAB/Simulink environment to evaluate its dynamic performance under varying load and renewable generation conditions. A supercapacitor is coordinated with existing converters to provide fast transient power support, helping to stabilize the DC bus voltage during sudden disturbances and mode transitions. Simulation results show improved DC bus voltage regulation and smoother transitions between operating modes. The main contribution of this work is demonstrating that significant improvements in transient stability and DC bus voltage regulation can be achieved in hybrid AC/DC microgrids through the coordinated operation of existing converters and energy storage elements, without introducing new control algorithms.*

***Keywords:*** *PV system microgrid energy coordination, grid control and operation, wind energy, supercapacitor.*

# ПОКРАЩЕННЯ ДИНАМІЧНИХ ХАРАКТЕРИСТИК ГІБРИДНОЇ AC/DC МІКРОМЕРЕЖІ ФОТОЕЛЕКТРИЧНИХ ТА ВІТРОВИХ УСТАНОВОК ЗАВДЯКИ УЗГОДЖЕНОМУ КЕРУВАННЮ З ВИКОРИСТАННЯМ СУПЕРКОНДЕНСАТОРА

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***Анотація.*** *У роботі представлено гібридну AC/DC мікромережу, розроблену з метою зменшення надлишкових перетворень електроенергії між системами змінного та постійного струму. Мережі змінного та постійного струму з'єднані між собою за допомогою двонапрямних перетворювачів, що забезпечує ефективний перетік потужності між ними та зменшує втрати на перетворення. Запропонована гібридна мікромережа працює у двох режимах: з приєднанням до електричної мережі та автономному. Відновлювані джерела енергії, навантаження та накопичувачі енергії підключені як до AC-, так і до DC-сторони системи відповідно до їхніх природних режимів роботи. Для оцінювання* *динамічних характеристик системи за змінних навантажень і режимів генерації з відновлюваних джерел енергії виконано її моделювання та імітаційні дослідження в середовищі MATLAB/Simulink. Суперконденсатор функціонує узгоджено з наявними перетворювачами, забезпечуючи швидку компенсацію перехідних потужностей, що сприяє стабілізації напруги DC-шини під час раптових збурень і переходів між режимами роботи. Результати моделювання засвідчили покращення регулювання напруги DC-шини та більш плавне перемикання між режимами функціонування. Наукова цінність роботи полягає в демонстрації того, що в гібридних AC/DC мікромережах можна досягти істотного підвищення перехідної стійкості та якості регулювання напруги DC-шини завдяки узгодженій роботі наявних перетворювачів і накопичувачів енергії без впровадження нових алгоритмів керування.*

***Ключові слова:*** *фотоелектрична мікромережа; координація енергетичних потоків; керування та експлуатація електричних мереж; вітроенергетика; суперконденсатор.*

**Introduction.** Due to their ability to operate at different voltage levels, their efficient long-distance power transmission capability, and their compatibility with rotating machinery driven by fossil-fuel energy sources, three-phase AC power systems have been used for a long time. Because of the natural issues presented by customary petroleum derivative power plants, sustainable energy systems are currently being connected to low voltage AC distribution systems as distributed generators or as AC microgrids. However, to conserve energy and reduce CO2 emissions, numerous DC loads, such as electric vehicles (EVs) and light-producing diode (LED) lighting systems, are connected to AC power systems. Power from nearby renewable energy sources eliminates the need for costly and tedious transmission of power over long distances at high voltages [1]. To facilitate integration of renewable energy sources into conventional AC systems, AC microgrids [2] - [5] have been proposed. To connect to the AC grid, DC/DC converters and DC/AC inverters are required to convert the DC power from energy components or photovoltaic (PV) panels into AC power. Many commercial and residential buildings rely on integrated AC/DC and DC/DC converters to meet their diverse DC power needs when connected to an alternating current grid. Controlling the speed of AC motors in industrial facilities is a common application of AC-DC-AC converters.

Renewable direct current power sources, together with the inherent advantages of direct current loads in a variety of applications (commercial, industrial, and residential), have recently contributed to the growing importance of DC grids. To include various distributed generators, the DC microgrid has been suggested in references [6] through [10]. Nevertheless, DC/AC inverters are necessary for the standard AC loads, and converting AC sources to DC is necessary before connecting to a DC grid.

The reason is that compared to a standalone AC or DC grid, managing, controlling, and operating a hybrid grid is more complex. Additionally, a hybrid AC/DC grid has many modes of operation. One way to reduce power losses while switching between alternating current and direct current networks is to coordinate the control of different converters. This would allow us to use renewable energy sources to their full potential. Unlike studies that focus on developing novel control algorithms or optimization techniques, this work emphasizes the coordinated operation of existing control schemes within a hybrid AC/DC microgrid. The central objective is to analyze how proper coordination among converters and energy storage elements, particularly the supercapacitor, can improve transient response, reduce DC bus voltage deviations, and enable smoother transitions between operating modes. This operational perspective provides practical insights into microgrid stability enhancement without increasing control complexity. This paper presents a coordinated control framework for a hybrid AC/DC microgrid in which the supercapacitor is deliberately prioritized for transient power compensation. Rather than modifying individual converter control laws, the proposed framework focuses on system-level coordination among existing controllers to enhance dynamic performance.

**Contributions of this work:**

The central objective of this study is to analyze how the coordinated operation of existing converters and a supercapacitor-based storage system can improve transient response and enable smoother transitions between operating modes. Specifically, this work seeks to demonstrate that prioritizing supercapacitors for fast transient compensation can reduce battery stress and maintain DC bus stability without the need for complex new control algorithms.

- Presentation of a coordinated control framework for a hybrid AC/DC microgrid that prioritizes supercapacitors for transient power compensation.
- Operational analysis of DC bus voltage stability under varying load and renewable generation conditions without introducing new control algorithms.
- Observation of reduced battery stress during transient events through coordinated utilization of supercapacitors.
- Evaluation of seamless mode transitions enabled by converter coordination in grid-connected and autonomous modes.

**Materials and Methods.** The research was conducted using MATLAB/Simulink R2024a to model and simulate a hybrid

AC/DC microgrid. The methodology involves mathematical modeling of renewable energy sources, including a PV array based on the single-diode circuit model and a 50 kW permanent magnet synchronous generator (PMSG)-based wind turbine. The control strategy employs standard PI controllers within a PQ control framework to regulate bus voltages during mode transitions. Data for solar irradiance and wind speed were integrated as time-varying inputs to evaluate the system's dynamic response under realistic fluctuations.

**System configuration and modeling.** This section describes the configuration of the proposed hybrid AC/DC microgrid and outlines the modeling assumptions used to evaluate its dynamic performance.

**Grid Configuration.** Fig. 1 illustrates the proposed hybrid AC/DC microgrid architecture integrating PV, wind generation, battery, and supercapacitor through coordinated bidirectional converters. The configuration enables selective prioritization of the supercapacitor during transient conditions, as implemented through coordinated converter operation described later. To interface DC sources, a DC boost converter is utilized. To represent a renewable generation sources, a 50 kW wind turbine generator (WTG) is connected to the AC bus through a grid-interfaced converter [11][12].

The energy storage unit consists of a 65 Ah battery connected to the DC bus through a bidirectional DC/DC converter. The variable load, ranging from 20 kW to 40 kW, is connected to both the DC bus and the AC buses, separately.

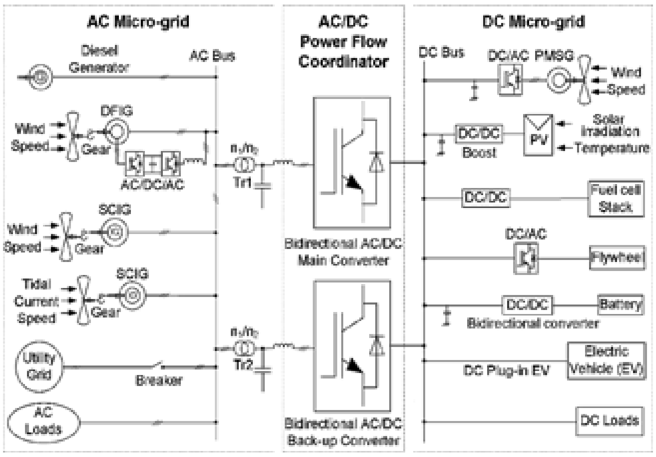

*Fig. 1. A hybrid AC/DC grid system*

The microgrid includes two types of buses: a DC bus with a rated voltage of 400 V and an AC bus with a rated voltage of 400 V rms[13].

**Operation of the grid**. The hybrid AC/DC microgrid operates under multiple predefined modes determined by grid availability, load demand, and renewable generation levels. The system operates in two principal modes. In the grid-connected mode, the converter enables power exchange between the AC and DC buses, maintains a consistent DC bus voltage, and provides reactive power support when required. When the generated power is insufficient to meet the load demand, the utility grid supplies the deficit. If the total generated power exceeds the demand, the excess electricity is fed back to the utility grid. In this operating mode, the battery converter plays only a minor role. Depending on the operating conditions, either the battery converter or the boost converter may be responsible for maintaining a constant DC bus voltage. A stable and reliable AC bus voltage is maintained by controlling the primary converter. The system functional requirements determine whether the PV array and the WTG operate in the off-MPPT mode or maximum power point tracking (MPPT) mode. To assess the MPPT control algorithm, the power output of the AC and DC sources is simulated by applying variable wind speed to the WTG and variable solar irradiance to the PV array, respectively [14]. The microgrid transitions through four distinct operating states:

- **Mode I:** Steady-state operation where PV generation meets the constant DC load demand and the DC bus voltage is maintained at 380 V, and the AC grid remains stable.
- **Mode II:** Transition triggered by a light load addition (e.g., 400 W), where the supercapacitor manages the initial voltage dip.
- **Mode III:** High-demand state (e.g., 1000 W load) where the bidirectional AC/DC converter enters rectification mode to draw power from the AC grid.
- **Mode IV:** Autonomous/Isolated state where the system must balance power using only internal energy storage during a grid fault.

**Coordinated Operation of Existing Converter Control Schemes.** In a hybrid grid, there are several kinds of converters. To supply variable DC and AC loads with uninterrupted power under changing conditions, such as variations in solar irradiance and wind speed, these converters should be properly controlled and coordinated with the utility grid. They should be capable of operating in both grid-connected and islanded modes. This subsection outlines the existing control schemes used by each converter and their coordinated operation within the hybrid microgrid.

**Grid-Connected Mode.** The PQ control method is implemented using a current-controlled voltage-source converter. PI control is employed to maintain a constant DC bus voltage despite variations in load demand and renewable energy generation conditions. The PI controller parameters are tuned to ensure stable and reliable system operation.

The converter is modulated when there is an abrupt reduction in DC demand, which results in excess DC power. During sudden load changes, voltage deviations may occur on the DC network. The primary converter is designed to transfer power from the AC side to the DC side. As a result, power can be supplied from the AC network to support the DC side.

**Modeling of the PV Panel.** Fig. 3 shows the equivalent circuit of a PV panel connected to a load. The output current of the PV panel is described by Equations (1)-(3) [11], [12].

$$I_{pv} = n_p I_{ph} - n_p I_{sat}\left[\exp\left(\frac{q}{AkT}\left(\frac{V_{pv}}{n_s} + I_{pv}R_s\right)\right) - 1\right] \tag{1}$$

$$I_{ph} = \left(I_{sso} + k_i(T - T_r)\right)\frac{S}{1000} \tag{2}$$

$$I_{sat} = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left(\frac{qE_{gap}}{kA}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right) \tag{3}$$

**In Equations 1–3, the variables are defined as follows:**

- I_{pv}: Output current of the PV panel.
- I_{ph}: Photocurrent, which is proportional to solar irradiance.
- I_{sat}: Reverse saturation current of the diode.
- n_p, n_s: Number of parallel and series-connected cells.
- q, k, A: Elementary charge, Boltzmann constant, and diode ideality factor.
- T, T_r: Cell temperature and reference temperature (Kelvin).

**Battery.** The hybrid grid operates in grid-connected mode, where the control objective of the boost converter is to regulate AC/DC/AC converter associated with the wind generation system. After that, the proposed method in [15] may be used to regulate the battery's DC/DC converter as an energy buffer. The primary converter is bidirectional and built to take advantage of the synergistic properties of wind and solar power [16], [17].

Power flow equations for both alternating current and direct current are written as follows:

$$P_{pv} + P_{ac} = P_{dcL} + P_b \tag{4}$$

$$P_s = P_w - P_{acL} - P_{ac} \tag{5}$$

The 50 kW WTG is connected to the AC bus and is represented by the power term Pw in Equation 5.

These equations are included to represent the power flow interactions between the AC and DC subsystems during dynamic operation.

In the proposed configuration, the battery primarily supports energy balancing, while the supercapacitor is prioritized for fast transient power compensation.

**Simulation results.** To test the suggested control algorithms, we model the hybrid grid's operations under different source and load scenarios. The transition mechanism between operating modes is illustrated in Fig. 2, which represents the simulation model used to analyze system behavior during mode changes. This section presents simulation results obtained under different load and renewable generation scenarios to evaluate DC bus voltage regulation, energy storage behavior, and mode transition performance of the proposed hybrid AC/DC microgrid. Multiple operating modes and transition cases are examined to assess the effectiveness of supercapacitor-assisted coordinated control under dynamic conditions.

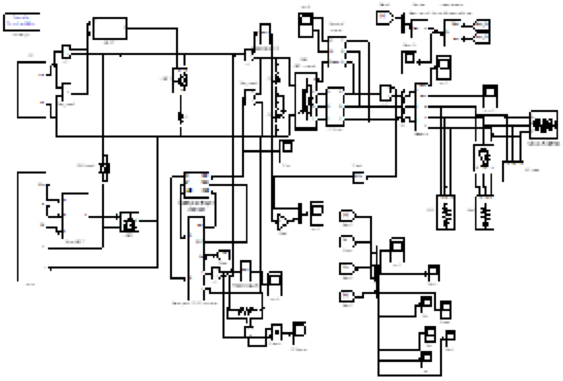

*Fig. 2. Simulation model for the transition from Mode I to Mode II*

The DC bus voltage remains close to its nominal value of 380 V during steady-state operation and transient conditions, as shown in Fig. 3. The corresponding load variations applied during the simulation are illustrated in Fig. 4. The variation in photovoltaic power output due to changes in irradiance is shown in Fig. 5. The power exchanged by the supercapacitor during transient events is shown in Fig. 6. The dynamic response of the hybrid AC/DC microgrid under varying load and photovoltaic generation conditions is simulated. Despite sudden load changes and renewable power fluctuations, the DC bus voltage remains close to its nominal value, indicating effective voltage regulation. The supercapacitor provides rapid transient power support, thereby mitigating power imbalances and enhancing overall system dynamic stability.

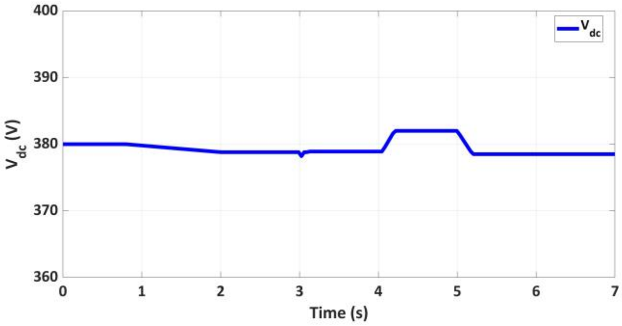

*Fig. 3. DC voltage versus time*

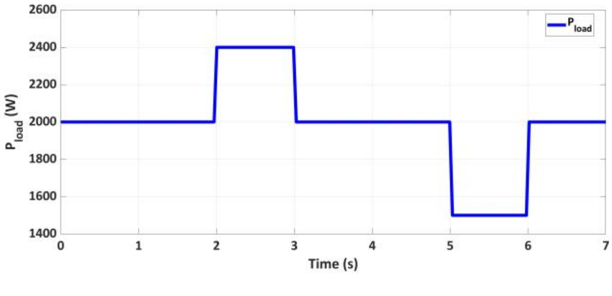

*Fig. 4. Load power versus time*

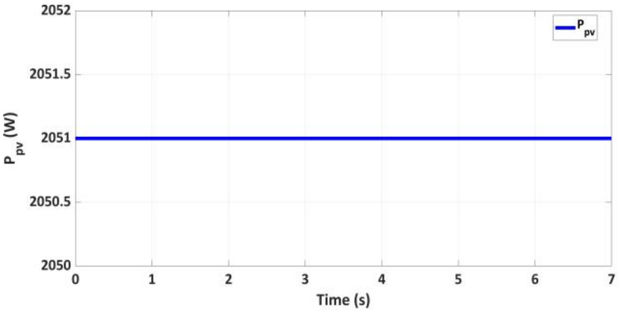

*Fig. 5. Solar power (watts) versus time*

Analysis: With a maximum of 2000 W, a temperature of 25 °C and an irradiance of 1 KW/m$^2$, the MPPT voltage is 180 V. The voltage of the power grid is 110 volts. The battery has a rated capacity of 90 Ah and a nominal voltage of 90 V. A supercapacitor with a capacitance of 12.5 F is connected in series with a resistance of 0.01 Ω. It is necessary to set the simulation sample time to 2 x 10$^{-6}$ s.

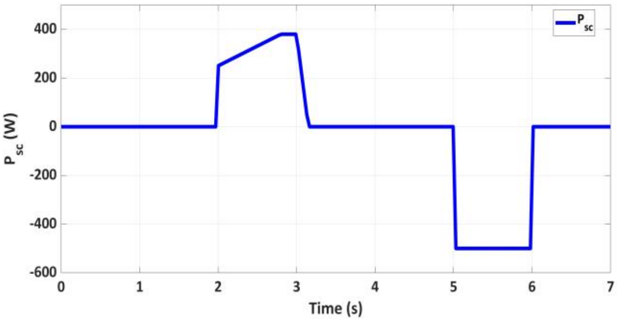

*Fig. 6. Power of the capacitor versus time*

Within six seconds, the system switches between two modes, mode I and mode II. There are one to four operations included. Changes in temperature and irradiance, or the introduction of a light load, will trigger the transitions. To start, the microgrid is up and running in 1-2 seconds, and the DC bus value is close to 380 V in the figures above, so the PV power that is delivered is sufficient to fulfill the need [18] - [22]. The voltage and current responses of the supercapacitor during mode transitions are shown in Figs. 7 and 8.

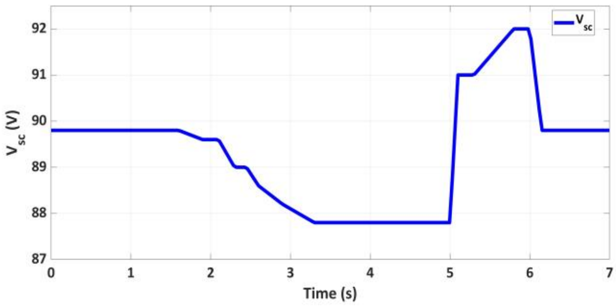

*Fig. 7. Voltage across the supercapacitor versus time*

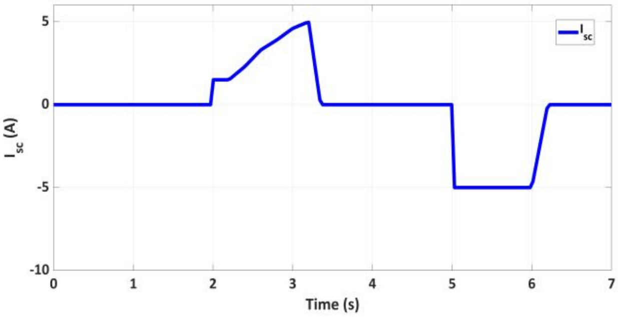

*Fig. 8. Current through the supercapacitor versus time*

The DC bus voltage would then fall to 377 V in 2 seconds under a 400 W load. During this time, the DC bus voltage is maintained by the supercapacitor's bidirectional DC/DC converter. Within three seconds, the 400 W load is disconnected from the system, and the DC bus voltage returns to 380 V. In 5 seconds, a 500 W load is disconnected, causing the DC bus voltage to rise to 383 V. The supercapacitor is utilized to store the excess energy during this time. The simulation model used to analyze the transition between Mode I and Mode III is shown in Fig. 9. The corresponding DC bus voltage, load power, and solar power responses for this operating condition are shown in Figs. 10–12.

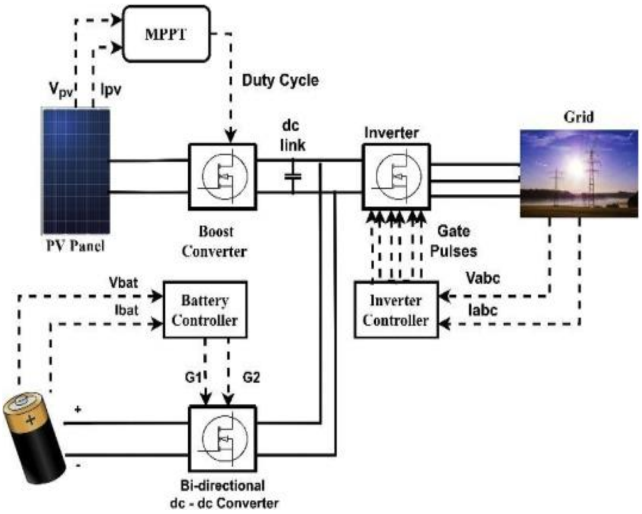

*Fig. 9. Block diagram for different transition processes*

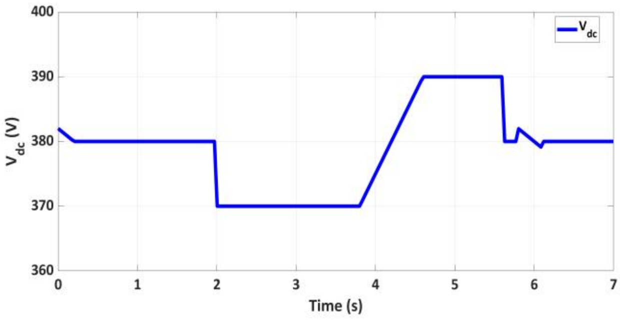

*Fig. 10. DC voltage versus time*

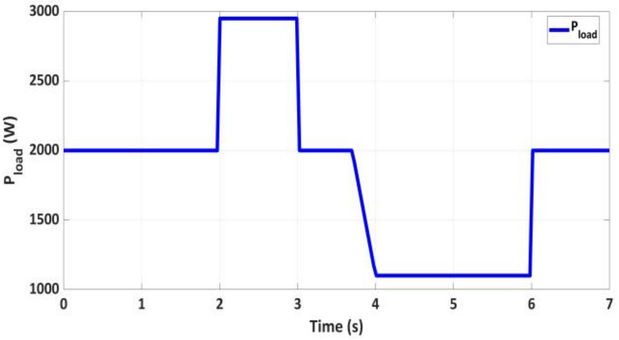

*Fig. 11. Load power versus time*

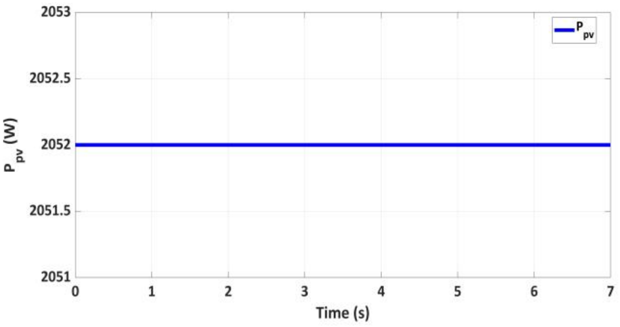

*Fig. 12. Solar power (watts) versus time*

Fig. 13 shows the simulation model for the transition between Mode II and Mode IV. The load power, battery response, and supercapacitor dynamics during this transition are shown in Figs. 14–18. During the transition between Mode II and Mode IV, the system experiences significant load variations and changes in power flow direction, creating transient power imbalances. The supercapacitor responds rapidly by supplying or absorbing power, thereby limiting DC bus voltage deviations during the transition period. In contrast, the battery exhibits smoother current and power profiles, indicating reduced involvement in fast transients. This coordinated behavior confirms that transient power compensation is effectively shifted toward the supercapacitor, reducing battery stress. As a result, stable operation and smooth mode transitions are achieved without modifying existing converter control schemes.

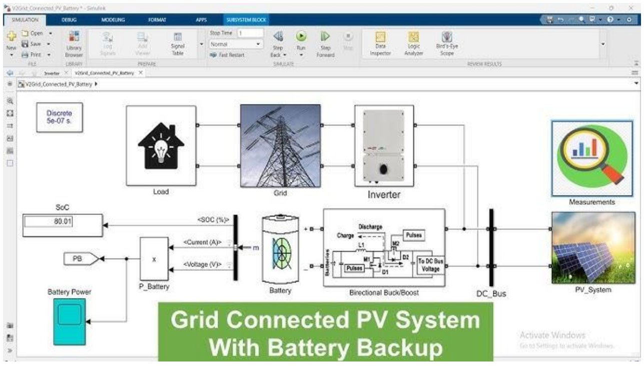

*Fig. 13. Simulation model for the transition between Mode II and Mode IV*

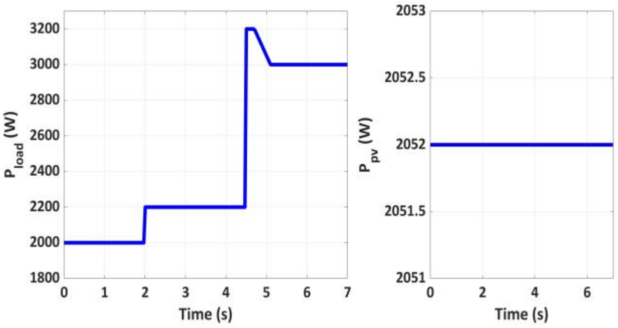

*Fig. 14. Load power, PV (solar power) versus time*

The corresponding transition is observed during the simulation. If the supercapacitor converter fails or if the energy stored in the supercapacitor is outside the allowable range, the corresponding system response is observed. Initially, the PV converter regulates the DC bus voltage at 380 V. At t = 2 s a 1000 W load is connected to the system, causing the grid-connected AC/DC converter to enter rectification mode and begin drawing power from the AC grid. During this period, the AC grid current and voltage remain synchronized. The grid converter maintains the DC bus voltage at 370 V. At t = 4 seconds, a 2000 W load is disconnected from the system, and at t = 4.8 seconds, the DC bus voltage reaches 390 V [23-25].

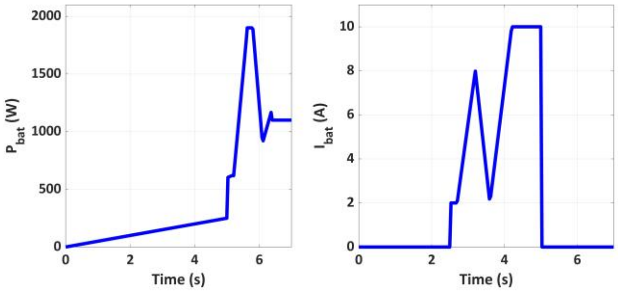

*Fig. 15. Battery power, current versus time*

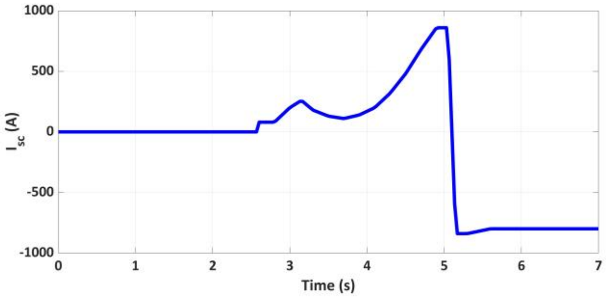

*Fig. 16. Current of the supercapacitor versus time*

If power is exported to the grid or the grid-connected converter fails, the DC bus voltage is regulated at 380 V by the PV converter. At t = 2 s, a 300 W load, and the DC bus voltage is maintained at 377 V by the supercapacitor's bidirectional DC/DC converter. At t = 4.5 s, a 1100 W load is connected to the system, causing the DC bus voltage to decrease to 365 V. At t = 7s, a 1400 W load is disconnected from the system, resulting in the DC bus voltage rising to 383 V.

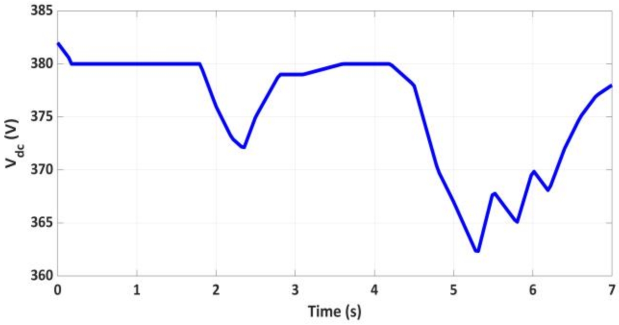

*Fig. 17. DC voltage across the supercapacitor versus time*

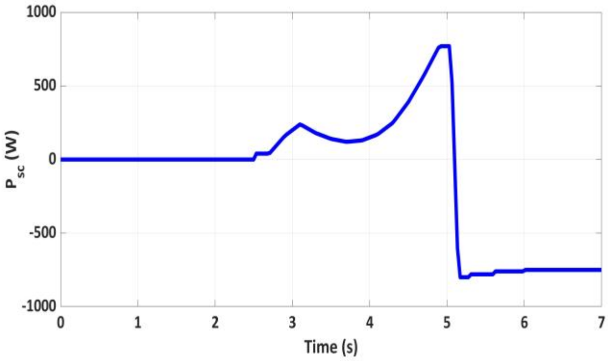

*Fig. 18. Power of the supercapacitor versus time*

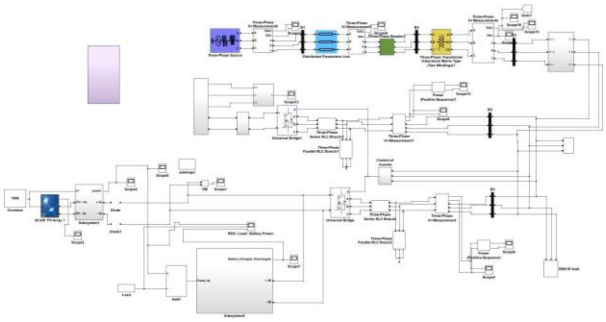

*Fig. 19. Simulation model for the transition from Mode I to Mode IV*

**Table. Comparison of Results**

| | I/P (V) | Load | Time | O/P (V) | |
|---|---|---|---|---|---|
| PV source | 380 V | 300 | 2 | 377 | Supercapacitor and Bi-directional DC-DC |
| | | 1100 | 4.5 | 365 | |
| | | 1400 | 3 | 383 | |

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