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ENERGY RECUPERATION AND REDISTRIBUTION IN REVERSIBLE AND BRAKING MODES OF DC MOTORS IN HYBRID AUTONOMOUS POWER SUPPLY SYSTEMS

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Abstract: Hybrid autonomous power supply systems increasingly combine renewable energy sources, energy storage units, power electronic converters, and electrically driven loads in order to improve energy efficiency and operational reliability. Within such systems, reversible direct-current (DC) motor drives can perform not only mechanical work but also operate in generating and regenerative braking modes. During deceleration or reversal, the kinetic and potential energy associated with the mechanical load can be converted into electrical energy and returned to the common DC bus or transferred to an energy storage system. This process is particularly important in autonomous systems where available generation capacity and stored energy are limited. The scientific literature demonstrates that hybrid energy storage systems based on batteries and supercapacitors are suitable for separating long-duration energy requirements from short-duration high-power transients. Supercapacitors provide high power density and rapid charge–discharge capability, while batteries provide comparatively higher energy density and are better suited to longer-duration energy exchange [1], [2]. Research on regenerative braking has demonstrated that appropriate energy-flow management can increase the utilization of recovered energy and reduce battery stress [3], [4]. This thesis examines the operating principles of reversible DC motor drives, regenerative braking, bidirectional power conversion, and energy redistribution in autonomous hybrid power systems. Particular attention is given to the coordination of batteries, supercapacitors, DC-link voltage regulation, and bidirectional converters.

Keywords: DC motor, regenerative braking, reversible drive, hybrid energy storage, autonomous power supply, supercapacitor, battery, DC bus, bidirectional converter, energy management.

Introduction

Autonomous electrical power systems are increasingly based on combinations of renewable energy sources and energy storage technologies. Photovoltaic and wind generation are characterized by variable power output, while electrical loads can change rapidly. Consequently, an autonomous system requires mechanisms capable of balancing generation, consumption, and stored energy. Hybrid energy storage systems have been developed specifically to combine storage technologies with complementary characteristics [1], [2].

A reversible DC motor provides an additional possibility for improving energy utilization. A conventional motor converts electrical energy into mechanical energy. Under appropriate operating conditions, however, the direction of power flow can be reversed: mechanical energy is converted into electrical energy and supplied back to the electrical system. During regenerative braking, the motor acts as a generator, producing electrical power while generating a braking torque [5], [6].

The four-quadrant operation of a DC drive is particularly relevant to reversible applications. A DC motor can operate in forward motoring, forward regenerative braking, reverse motoring, and reverse regenerative braking modes. Four-quadrant operation therefore provides independent control of the direction of motor speed and electromagnetic torque [7], [8].

In an autonomous hybrid system, recovered energy cannot simply be regarded as an additional energy source without considering the state of the DC bus and the storage devices. The recovered electrical energy must be appropriately distributed. Depending on the instantaneous operating condition, it may supply an active load, charge a supercapacitor, charge a battery, or be transferred to another electrical subsystem. Therefore, regenerative braking should be considered as part of an integrated energy-management strategy rather than as an isolated motor-control function.

Methodology

The thesis is based on a comparative analysis of published scientific research concerning reversible DC drives, regenerative braking, hybrid battery–supercapacitor energy storage, DC microgrids, and

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bidirectional power conversion. The methodological framework combines electrical-machine theory, energy-flow analysis, and control-system principles.

For a separately excited DC motor, the principal electrical relationships can be expressed as:

$$V_a=E_a+I_aR_a+L_a\frac{dI_a}{dt}$$

where V_a is armature voltage, E_a is back electromotive force, I_a is armature current, R_a is armature resistance, and L_a is armature inductance.

The electromagnetic torque can be represented by:

$$T_e=k\Phi I_a$$

where k is the motor constant and Φ represents magnetic flux.

The mechanical dynamics are described by:

$$J\frac{d\omega}{dt}=T_e-T_L-B\omega$$

where J is the equivalent moment of inertia, ω is angular velocity, T_L is load torque, and B is the viscous-friction coefficient.

During regenerative braking, the electromagnetic torque acts opposite to the direction of rotation. Mechanical energy is therefore converted into electrical energy. For a rotating system, the available kinetic energy is associated with:

$$E_k=\frac{1}{2}J\omega^2$$

The actual recovered electrical energy is lower than the available mechanical energy because losses occur in the motor, converter, cables, storage devices, and other components. Research on regenerative braking specifically emphasizes the importance of evaluating the complete energy-transfer path rather than considering only motor-side energy conversion [3].

A hybrid storage configuration normally combines a battery and supercapacitor. The battery is used primarily for energy-intensive, comparatively slow power exchange, whereas the supercapacitor is suitable for short-duration high-power events. Experimental and analytical research has demonstrated that this complementary behavior can be useful for fluctuating renewable generation and pulsed loads [1], [2].

The investigated energy-flow structure can therefore be represented conceptually as:

Renewable sources → DC bus → bidirectional converter → DC motor / load

with the battery and supercapacitor connected to the DC bus through appropriate power-electronic interfaces.

During motoring, energy flows from the storage system and/or renewable sources toward the motor. During regenerative braking, the direction of energy flow changes:

Mechanical load → DC motor-generator → converter → DC bus → supercapacitor/battery/load.

Such bidirectional operation requires a power converter capable of controlling both directions of current and power.

Results

The analysis demonstrates that reversible DC motor drives can provide an important energy-recovery function in autonomous hybrid electrical systems. The fundamental advantage is that braking energy does not necessarily have to be dissipated entirely as heat. Instead, a portion of the mechanical energy can be transformed into electrical energy and subsequently reused.

The four-quadrant operating principle is particularly important. In forward motoring, motor speed and electromagnetic torque have the same sign. In regenerative braking, their signs are opposite. The same principle applies during reverse operation. Literature on DC drives explicitly identifies regenerative braking in both rotational directions as a characteristic of four-quadrant operation [7], [8].

Hybrid storage significantly improves the ability of the electrical system to accommodate regenerative power. Supercapacitors are characterized by high power density and rapid

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charge/discharge capability. A study of battery–supercapacitor storage for remote renewable systems reported supercapacitor power densities of approximately 1000–5000 W/kg and charge/discharge efficiency around 95%, while emphasizing their suitability for rapid power fluctuations [1]. The same study identified batteries as better suited to longer-duration energy management [1].

The combination of the two storage technologies is therefore particularly relevant to regenerative braking. A short-duration braking event may generate a high instantaneous power level, while the total energy associated with the event may be comparatively limited. The supercapacitor can absorb this rapid power pulse, after which energy can be transferred more gradually to the battery or consumed by the local electrical load.

Experimental research on supercapacitor-based regenerative braking has reported regenerative energy conversion efficiency of up to 88% under the investigated operating conditions [4]. This result should not be interpreted as a universal efficiency value for all regenerative braking systems, because the actual recovery efficiency depends on vehicle or machine speed, braking conditions, converter losses, storage state, control strategy, and other system parameters.

Research on hybrid energy storage has also shown that the energy-flow strategy has a direct influence on overall utilization efficiency. Energy losses occur during motor-generator conversion, DC/DC conversion, battery charging, supercapacitor charging, and subsequent energy discharge [3]. Consequently, maximizing recovered energy requires simultaneous consideration of the efficiency of individual components and the operating state of the complete system.

Research on DC microgrids has demonstrated that coordinated battery–supercapacitor control can reduce battery charge/discharge frequency and improve DC-bus stability [9]. The supercapacitor can respond rapidly to transient disturbances, while the battery can provide slower energy balancing.

The integration of regenerative braking into a DC microgrid has also been investigated for railway applications. A published study considered a system consisting of photovoltaic generation, hybrid battery–supercapacitor storage, DC loads, and regenerative braking. The recovered braking energy was directed toward the supercapacitor, which was selected for its ability to handle short-duration power bursts [10].

Analysis and Discussion

The principal technical challenge is not the conversion of mechanical braking energy into electricity itself, but the appropriate management of the resulting electrical power. If the storage system cannot accept the recovered energy, the DC-bus voltage may increase. Therefore, the control system must monitor DC-bus voltage, motor speed, motor current, battery state of charge, supercapacitor voltage, and allowable converter current.

The battery and supercapacitor should not necessarily receive identical portions of recovered energy. Their physical characteristics are fundamentally different. Batteries are primarily energy-oriented devices, whereas supercapacitors are power-oriented devices [1], [2]. This difference supports a hierarchical energy-management strategy.

During a high-power braking event, the supercapacitor can initially absorb the transient component. Once the braking event ends, the stored energy can either remain available for the next acceleration event or be transferred gradually to the battery. This approach reduces the requirement for the battery to absorb high-frequency power fluctuations.

The literature also demonstrates that hybrid-storage topology affects system complexity. Passive battery–supercapacitor configurations are relatively simple, whereas fully active configurations require additional DC/DC converters and more sophisticated control systems [2]. Semi-active configurations provide an intermediate solution between simplicity and controllability.

Control methodology is another important factor. Conventional PI controllers are widely used for DC-bus voltage and motor speed regulation. More advanced strategies, including robust control and nonlinear control, have also been investigated. A study using H_∞ control for a battery–supercapacitor system demonstrated real-time power-management functionality and DC-bus regulation while maintaining supercapacitor voltage within a controlled operating range [11].

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The energy-management system should therefore establish priorities. When the motor is accelerating, stored energy is supplied to the DC bus. During regenerative braking, recovered energy is first directed toward loads and high-power storage where technically appropriate. When the supercapacitor reaches a defined state of charge or voltage limit, additional recovered energy may be transferred toward the battery, provided that battery charging limits permit this.

The state of charge of the battery is another essential variable. DC-microgrid research has demonstrated control strategies in which battery state of charge is used to determine whether the battery should participate actively in energy exchange, while the supercapacitor handles rapid DC-bus fluctuations [9].

The principle is particularly relevant for autonomous systems because renewable generation cannot always absorb or compensate for instantaneous power changes. If the autonomous source is producing less power than required by the load, stored energy supplies the deficit. Conversely, when regenerative braking produces additional electrical power, that energy can reduce the demand on the renewable source or recharge the storage system.

Recent research continues to support this concept. A 2025 study of a hybrid energy-storage unit for regenerative braking used a battery–supercapacitor architecture and investigated power allocation between the two storage elements during acceleration and regenerative braking. The study emphasized the complementary roles of battery and supercapacitor and experimentally verified the control structure [12].

The overall energy balance of the autonomous system can be expressed conceptually as:

$$P_{RES}+P_{storage}+P_{regen}=P_{load}+P_{loss}$$

where P_{RES} is renewable generation, $P_{storage}$ is storage-system power, P_{regen} is regenerative power, $P_{load}$is load power, and P_{loss}represents system losses.

This relationship illustrates why regenerative braking can improve the utilization of an autonomous energy system. Recovered energy effectively becomes an internal source of electrical energy rather than being completely dissipated in mechanical or resistive braking.

Conclusion

Reversible DC motor drives provide an effective mechanism for recovering mechanical energy during braking and redistributing it within hybrid autonomous electrical systems. Four-quadrant operation allows a DC motor to operate in both motoring and regenerative modes in forward and reverse directions. During regenerative braking, mechanical energy is converted into electrical energy and transferred through a bidirectional converter toward the DC bus and available storage or electrical loads.

The reviewed literature confirms the complementary characteristics of batteries and supercapacitors. Batteries provide comparatively high energy-storage capability, whereas supercapacitors are particularly suitable for rapid high-power charging and discharging [1], [2]. Consequently, hybrid battery–supercapacitor storage is technically suitable for absorbing the short-duration power pulses generated during regenerative braking.

The effectiveness of the complete system depends on coordinated control of motor torque, DC-bus voltage, converter current, battery state of charge, and supercapacitor voltage. Experimental research has demonstrated regenerative conversion efficiencies as high as 88% under specific investigated conditions [4], while other studies have demonstrated the advantages of coordinated hybrid-storage control for DC microgrids and regenerative braking applications [3], [9], [10].

Therefore, energy recuperation from reversible DC motor drives should be treated as an integrated energy-management function of the autonomous power supply system. Appropriate power allocation can increase the utilization of recovered energy, reduce unnecessary battery stress, stabilize the DC bus, and improve the overall energy efficiency of the hybrid system.

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