

Review

Hybrid-Actuated Linkage Mechanisms: Design, Control, and Energy Management

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Abstract

Hybrid-actuated linkage mechanisms combine a main drive with a controllable auxiliary input to shape motion while distributing actuator demand. This narrative review examines mechanism design, control strategies, and energy management for presses and related cyclic machinery. The mechanisms are grouped into five-bar, seven-bar, slider-crank and differential, and application-specific configurations. The synthesis identifies trade-offs among motion programmability, dwell generation, actuator loading, and structural complexity; it does not establish a universal ranking of topologies. Control methods are compared by function, including local feedback, adaptation and iterative learning, disturbance rejection, predictive optimization, and position–force or position–pressure switching. Energy measures are distinguished as demand shaping, loss reduction, regeneration, storage, and auxiliary harvesting. Press and die-cushion studies provide application-relevant evidence, whereas many robotic, vehicle, and vibration-harvesting studies provide transferable principles requiring further validation. Reported servo-energy shares, torque reductions, installed power, and energy per cycle cannot be compared as equivalent efficiency indicators. An integrated design framework links mechanism selection, control organization, and energy flow across the operating cycle. Future comparisons require common forming tasks, explicit energy-accounting boundaries, and experimental validation of coupled mechanical, control, and storage decisions.

Keywords: hybrid-actuated linkage; hybrid servo press; mechanism synthesis; motion control; energy recovery; flywheel; hydraulic accumulator; integrated design



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1. Introduction

Linkage mechanisms transmit motion and forces through connected links and joints. Their kinematic behavior depends on topology, geometry, and input motion; neither constant transmission ratio nor high efficiency follows from the use of links alone. Planar mechanisms are widely used in presses, handling equipment, and manipulators because their geometry can be selected to generate a required output path or motion law [1,2].

Mechanism classification and structural synthesis provide the basis for selecting a suitable linkage [3–6]. For press applications, the relevant questions are how the work-

ing stroke is generated, how force is transmitted near the forming region, and how the mechanism responds to clearance, load variation, and changing production requirements.

Planar closed-chain mechanisms offer several routes to motion generation. Studies of five-bar mechanisms, slider-crank dynamics, and higher-class press linkages illustrate the different trade-offs between topology, transmission characteristics, and dynamic response [7–13]. Spatial and compliant mechanisms broaden this design space, but their performance should not be assumed to represent that of a planar metal-forming press.

A fixed-geometry, single-input mechanism constrains the relationship between input and output motion. Adding an independently controlled input can expand the available motion profiles but also introduces coupling between actuators and additional control requirements. Hybrid actuation is therefore a joint mechanism-and-control problem rather than a motor substitution alone [14–16].

In this review, hybrid-actuated linkages primarily denote mechanisms in which a constant-speed main drive and a servomotor contribute coordinated inputs. The term is distinct from hybrid-electric vehicle propulsion, from a hybrid control algorithm, and from systems combining different actuator technologies. Those adjacent concepts are discussed only where they clarify a transferable physical or control principle.

The control problem involves tracking the required output motion while respecting actuator limits and maintaining coordination during free motion, contact, forming, and return. The energy problem concerns the distribution of work and losses between the main drive, servo drive, transmission, and any storage or regenerative path. Improved tracking, lower peak torque, and lower electrical energy consumption are separate outcomes that require separate measurements.

This review brings together linkage design, control organization, and energy-management approaches for presses and related cyclic systems. It asks which mechanism features enable useful motion profiles, which control functions are needed in each operating phase, and which energy measures are supported by press-specific evidence. Sections 3–5 synthesize the three topic areas; Section 6 integrates their implications and limitations; Section 7 presents the conclusions.

2. Review Method and Scope

This study is organized as a narrative review of three connected areas: hybrid-actuated linkage mechanisms, control methods for coupled actuators and press systems, and energy management in cyclic machinery. The synthesis is qualitative because the studies differ in machine scale, load, duty cycle, system boundary, and validation method. No statistical meta-analysis or pooled efficiency estimate is presented.

2.1. Literature Identification

The literature search covered Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar, supplemented by reference-list screening and citation chaining. The main search window was January 2015 to September 2026. Earlier seminal publications were retained when required to establish mechanism classification, the development of hybrid-driven presses, or established control principles.

Representative search strings, adapted to the syntax of each database, were: (i) (“hybrid-actuated” OR “hybrid-driven” OR “controllable mechanism” OR “hybrid servo press”) AND (linkage OR mechanism OR press OR forming); (ii) (“servo press” OR “hybrid press” OR “hybrid linkage” OR “die cushion”) AND (PID OR “model predictive control” OR MPC OR adaptive OR “iterative learning” OR “sliding mode” OR “position force” OR “position pressure”); and (iii) (press OR “servo press” OR “hydraulic press” OR “cyclic

machinery”) AND (“energy saving” OR regeneration OR “energy recovery” OR flywheel OR accumulator OR supercapacitor OR “passive balancing” OR “vibration harvesting”).

Publications were considered eligible when they: (i) addressed the design, modeling, control, optimization, or energy performance of a hybrid-actuated linkage, press, press-related subsystem, or technically transferable actuator system; (ii) provided an identifiable mechanism, control strategy, energy architecture, or evaluation procedure; and (iii) reported analytical, numerical, simulation-based, experimental, industrial, or quantitatively interpretable findings. Foundational books and selected technical documents were retained for terminology, historical context, or industrial implementation examples. Records were not retained when they duplicated another publication, used the term “hybrid” in an unrelated sense, lacked sufficient technical relevance to the review questions, or did not provide an identifiable technical method or evidence boundary.

The working reference library contained 205 records after adding the two reviewer-recommended studies on composite hydraulic-cylinder components. Duplicate screening identified two repeated records, leaving 203 unique records for relevance and bibliographic assessment. Fourteen records were not retained because they did not meet the final relevance or completeness criteria. Consequently, the revised review corpus included 189 publications.

2.2. Scope and Evidence Classification

The review covers studies on mechanism design, modeling, control, and energy performance. Foundational books provide terminology and theoretical background. The review discusses studies from related application domains when they offer concepts potentially transferable to press systems, while explicitly acknowledging differences in operating conditions and application requirements.

The studies are discussed in two complementary terms: their relevance to press applications and the type of evidence supporting their findings. Application relevance distinguishes studies of complete press systems, relevant subsystems such as die cushions and hydraulic servo axes, and other applications such as robots, vehicles, and vibration harvesters. Analytical and numerical findings are distinguished from experimental results. Simulation studies of press systems provide application-relevant insights, but simulation results alone do not constitute experimental validation. The retained publications were coded according to publication period, application relevance, and dominant validation type. To avoid double counting, each publication was assigned to one primary category within each classification dimension. Table 1 summarizes the distribution of the 189 retained publications.

Table 1. Distribution of the retained review corpus (N = 189).

Dimension	Category	n (%)
Publication period	Before 2015	12 (6.3%)
	2015–2019	26 (13.8%)
	2020–2022	67 (35.4%)
	2023–2026	84 (44.4%)
Application relevance	Direct press-specific evidence	24 (12.7%)
	Press-adjacent industrial or mechanism-level evidence	45 (23.8%)
	Transferable evidence from robotics, vehicles, and energy systems	114 (60.3%)
	Foundational or general sources	6 (3.2%)
Dominant validation type	Review or foundational synthesis	43 (22.8%)
	Analytical, numerical, or simulation-based	82 (43.4%)
	Experimental, prototype, industrial, or mixed validation	64 (33.9%)

2.3. Comparative Synthesis and Limitations

Using the review corpus summarized in Table 1, mechanisms were compared by topology, input arrangement, motion capability, and actuator demand. Control methods are compared by functional role, controlled variable, and implementation constraints. Energy approaches are compared by physical function and by the operating phase in which energy is consumed, stored, dissipated, or recovered. The comparative tables and integrated framework are a qualitative synthesis, rather than a quantitative ranking.

Energy per cycle, peak torque, installed power, recovered energy, and servo-energy share are treated as distinct indicators. Comparisons require a stated reference machine, load, motion profile, and energy-accounting boundary. The narrative design may introduce selection bias, and the absence of a common benchmark limits conclusions about relative superiority. The proposed design framework therefore identifies hypotheses and evaluation priorities for subsequent press-specific testing.

3. Hybrid-Actuated Linkage Mechanisms

A hybrid-actuated linkage combines coordinated actuator inputs within a common mechanical system. In the press configurations emphasized here, a main motor supplies the principal cyclic motion and a servomotor modifies the output trajectory. This arrangement can reduce the required servo capacity for a suitable motion and load, but the actual power split depends on geometry, transmission ratios, and the operating cycle [16–18].

Press motion commonly includes approach, a forming interval, and return. A second input allows these phases to be shaped within the feasible workspace and actuator limits. Motion design can influence forming conditions and cycle time, as investigated for hybrid servo presses [19]. Improved part quality or productivity remains process-dependent and should not be claimed for every hybrid architecture.

Two-input linkages and differential-coupled drives are alternative ways to combine actuator motions. In a linkage, independently driven joints contribute through the closed kinematic chain; in a differential arrangement, motions are combined in a transmission. These categories can overlap in a complete machine. Their efficiency must be evaluated from the actual torque, speed, and power flows rather than inferred from the label “hybrid” [16,20,21].

Figure 1 illustrates a seven-bar mechanism with two inputs [20]. Its output depends on both input coordinates. The servomotor may supply or absorb power during different phases; describing its contribution as universally low-torque or high-frequency would obscure this dependence. Link dimensions and input trajectories must be synthesized together to obtain the required ram motion.

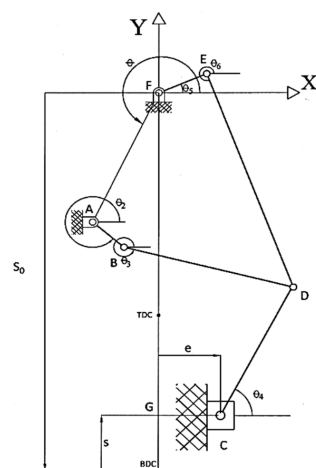


Figure 1. Two-input seven-bar mechanism. (Adapted from Kütük et al. [20], Figure 1, under the CC BY 3.0 license.).

The same coordination principle appears in non-press machinery, including hybrid textile transmissions [22]. Such applications establish the usefulness of motion modulation, but their loads and performance measures differ from those of stamping and forging presses.

Kinematic models relate the input coordinates to the output path; dynamic models add inertia, external load, and losses. For coupled drives, output tracking depends on both individual axis performance and relative phase accuracy. Researchers have investigated iteration-based tracking and adaptive control for hybrid machines and closed-chain five-bar systems [14,15].

3.1. Five-Bar Hybrid Mechanisms

A planar five-bar closed chain can provide two independently actuated inputs and programmable motion of a selected output point. Its compact topology is attractive for positioning and handling, while the usable workspace and transmission quality depend on geometry and assembly mode. Simulation and control studies support hybrid five-bar systems [7,15,17].

Geometric synthesis determines which trajectories are feasible and how actuator loads change along them. The five-bar configuration can be combined with auxiliary links to convert point motion into a press stroke. Mechanism-level tracking results should therefore be distinguished from a demonstration of forming capacity under a specified press load.

Both inputs act through the same closed chain, so synchronization errors can affect output accuracy and internal loading. Controller design should account for the coupled dynamics and for singular or poorly conditioned configurations. Because both actuators close through the same kinematic chain, a synchronization error changes not only the output position but also the internal constraint state. The resulting output error is governed locally by the mechanism sensitivity and may be strongly amplified near singular or poorly conditioned configurations. Internal mechanical stress cannot be inferred from output error alone; it also depends on joint and link compliance, clearance, constraint reactions, and the applied forming load [7,15,17,23,24]. Consequently, press-scale assessment requires a loaded dynamic or elastodynamic model together with experimental strain, reaction-force, or torque measurements. Compactness alone does not establish stiffness, energy efficiency, or suitability for high-load forming.

Compactness should therefore be treated as a packaging advantage rather than as proof of structural capacity. Suitability for high-load forming must be demonstrated through link and joint stress, elastic deflection, transmission quality, bearing and guide reactions, local buckling, fatigue, frame compliance, and experimental loading under the intended forming-force history. The available five-bar studies establish motion-generation and control potential, but heavy-press capacity remains topology- and dimension-specific.

3.2. Seven-Bar Hybrid Press Mechanisms

Seven-bar arrangements add links and constraints that can convert coordinated rotary inputs into a useful ram stroke. They provide more synthesis variables than simpler configurations, at the cost of additional joints and modeling complexity. Li and Zhang and Kütük et al. have investigated press-oriented kinematic design and optimization [16,24].

The design problem includes matching forming displacement and velocity requirements while respecting link geometry and transmission constraints. A useful low-speed interval near the forming zone must be evaluated together with the remaining stroke, input-speed requirements, and actuator loading. A kinematically feasible trajectory may still be dynamically impractical.

A low-speed forming trajectory should be accepted only after verifying it over the complete production cycle. The assessment should include input speed and acceleration,

peak and root-mean-square torque, actuator torque-speed limits, inertial and joint loads, transmission quality, vibration, clearance and friction effects, cycle time, and thermal duty during approach, forming, dwell, and return. A motion law that is favorable near bottom dead center may still be dynamically impractical at production speed elsewhere in the cycle.

A low-velocity or dwell interval can result from the combined choice of geometry and input motion. It is not an automatic property of every seven-bar mechanism, nor does a stationary ram imply zero servo torque or zero electrical consumption. Dwell quality and duration should be reported with the required input motion, loading, and actuator effort [16,25].

Ram dwell constrains the output motion but does not uniquely determine the internal actuator state. The required servo torque must be obtained from the loaded dynamic equilibrium of the complete mechanism, including the actual workpiece-force history, inertia, friction, clearance, and transmission losses. Instantaneous servo mechanical power is the product of servo torque and servo angular velocity, while electrical input additionally includes motor, converter, and holding losses. Dwell performance should therefore be reported with peak and root-mean-square servo torque, servo speed, electrical power, thermal duty, and the applied forming load, rather than assuming zero power at zero ram speed.

Kütük et al. optimized link dimensions using a genetic algorithm and then performed a kinetostatic analysis for a stamping motion with a dwell [25]. The study supports the importance of geometric synthesis and load analysis. This study does not infer a general percentage reduction in servo torque without an explicitly identified baseline and numerical comparison.

Hybrid-machine tracking studies provide complementary control evidence [14,15]. Their specific topologies and validation conditions should be retained when discussing transfer to seven-bar presses. Dynamic simulations of press mechanisms also support actuator sizing and control development, but require validation of load, friction, and clearance assumptions [26].

The flywheel-assisted press studied by Tso and Li provides direct blanking-test evidence of energy partition between the drives [18]. The reported servo share was approximately 12% of total stamping energy. This does not establish the electrical energy of the entire production cycle, which may also include approach, return, idle operation, auxiliary equipment, and drive losses.

Reprogramming a servo input can change the available ram trajectory within the machine's geometric and actuator limits. Kinematic modeling of seven-bar linkages provides a basis for this design task [27]. Claims about tool life, operating cost, and product quality require measurements for the particular forming process.

3.3. Slider-Crank and Differential-Based Arrangements

Slider-crank and differential-based arrangements build on familiar reciprocating transmissions. An auxiliary input can modify the effective relationship between crank motion and slider displacement. Designs for nonuniform motion illustrate this approach [21]. Retrofit suitability depends on the specific transmission and cannot be established solely from a shared slider-crank description.

The integration point of the second actuator determines the available motion modulation and internal power flow. Rotary differentials and auxiliary linkage inputs can produce different torque and speed demands even when their output strokes appear similar. A useful comparison therefore needs the complete topology and both input trajectories.

A fair comparison should impose the same ram displacement, velocity, forming-force history, cycle time, workpiece, and actuator constraints. It should then report both input tra-

jectories, peak and root-mean-square torque, maximum speed, instantaneous and integrated branch power, internal power circulation, thermal duty, regeneration, and net electrical energy. Similar output strokes do not imply comparable actuator or loss requirements.

Prolonged low-speed operation or dwell may require substantial corrective motion from the auxiliary drive in some configurations. Opposing actuator torques do not by themselves quantify energy loss: mechanical power depends on torque and speed, and an electrical drive may regenerate, dissipate, or recirculate the associated energy. The energy balance must include these paths.

In differential and auxiliary-input arrangements, the instantaneous powers of the two drive branches may be large and opposite while the net output power remains small. Such internal power circulation is not automatically a loss because one drive may regenerate to the other drive or to the common electrical bus. However, prolonged low-speed or holding phases can still produce high current, copper loss, converter loss, frictional dissipation, and thermal loading. Therefore, the power, torque, speed, and energy of each branch should be evaluated separately for the selected integration topology.

The design trade-off is between preserving a conventional transmission and obtaining a wider programmable-motion range. Required servo torque, speed, thermal duty, and control authority should be checked over the intended production cycle. Flywheel-assisted seven-bar evidence is not assigned to the slider-crank category merely because the complete machine contains a crank and a slider.

3.4. Application-Specific Hybrid Actuation

Additional links, compliant elements, and alternative actuator technologies extend the range of hybrid systems. However, an application-specific actuator combination should be distinguished from the constant-speed-motor/servomotor press architecture. Similar terminology does not imply equivalent load capacity, motion transmission, or energy efficiency.

A hybrid-driven combi detaching-roller transmission illustrates coordinated inputs in textile machinery [22]. Its comparison of input schemes is relevant to transmission design, while its textile operating conditions remain distinct from high-force metal forming.

Low et al. investigated a finger prosthesis combining a DC motor and a shape-memory-alloy actuator with tactile sensing [28]. Figure 2 shows its structure. Roshanfar et al. studied a hybrid-actuated soft robot using a Cosserat-rod model [29]. These examples combine actuator technologies and are included as adjacent applications rather than performance evidence.

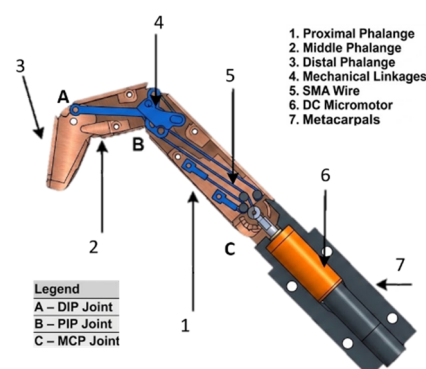


Figure 2. Internal structure of a hybrid-actuated finger prosthesis. (Adapted from Low et al. [28], Figure 5, under the CC BY 3.0 license. Colors and annotations modified. © 2013 Low et al.).

Advances in linkage design and hybrid actuation have contributed to more flexible and programmable forming machinery. Jomartov, Halicioglu, and Kuatova manufactured and experimentally tested a press prototype based on the Stephenson II mechanism and

compared its measured performance with kinetostatic predictions. Their results demonstrated improved force distribution on the slider and reduced reactions at the slider guides, supporting the practical benefits of the proposed mechanism design [30]. In related work, Tuleshov et al. developed an analytical kinematic model of a hybrid seven-bar linkage driven by a constant-speed motor and a servomotor. Incorporating a coulisse mechanism enabled programmable output motion, providing a basis for trajectory design in hybrid presses [27]. Together, these studies illustrate how experimental verification and kinematic modeling support the development of advanced press mechanisms with improved mechanical performance and greater motion flexibility.

Clearances can influence the dynamic response and accuracy of closed-chain mechanisms [23,24]. Other studies consider a special five-bar mechanism for a shield machine, peak-staggered press-linkage design, and a seven-bar disinfection robot [31–33]. These contributions inform modeling and synthesis, while their application and validation boundaries remain distinct.

Furthermore, a critical emerging trend in application-specific actuation is the integration of composite actuators [34,35]. These advanced materials are well suited to hybrid linkage mechanisms because they offer tunable mechanical compliance, high force-to-weight ratios, and inherent damping. Incorporating composite materials bridges the gap between conventional rigid servo-driven linkages and next-generation compliant mechanisms, offering fundamentally new ways to manage dynamic response and load distribution during the forming process.

3.5. Comparative Synthesis of Mechanism Architectures

Table 2 compares actuator integration, motion capability, and principal limitations. It separates press-oriented studies from evidence obtained in other machinery. More links may increase motion-shaping freedom but also add design parameters, joints, and potential error sources. No topology can be ranked independently of the required stroke, forming load, and actuator constraints.

Table 2. Comparative assessment of the hybrid-actuated linkage architectures reviewed in this study.

Architecture	Motion and Integration	Principal Limitations	Evidence
Five-bar linkage	Compact closed chain with two coordinated inputs; programmable planar output.	Coupled tracking, workspace, and singularity constraints; load capacity is design-specific.	Hybrid-mechanism simulation and control [7,15,17].
Seven-bar press linkage	Additional synthesis freedom for ram motion and low-speed intervals.	More joints and parameters; dwell quality and actuator effort require joint evaluation.	Press-oriented kinematics and kinetostatics [16,25]; flywheel-assisted blanking [18].
Differential or auxiliary-input arrangement	Combines drive motions within a transmission or modified linkage.	Corrective torque, speed, power circulation, and retrofit practicality depend on integration.	Nonuniform-motion design [21]; topology-specific verification required.
Application-specific hybrid actuation	Combines inputs or actuator technologies for a specialized task.	Different loads, compliance, and energy boundaries limit transfer to presses.	Textile transmission, prosthesis, soft robot, and other mechanisms [22,28,29,31,33].

Five-bar systems offer a compact basis for programmable planar motion. Seven-bar press configurations provide additional freedom to shape ram motion. Differential and auxiliary-input arrangements may retain more of an existing transmission. These are design considerations, not a pooled experimental ranking of efficiency or forming capacity.

Energy and torque metrics must remain separate. A servo share of stamping energy, as reported by Tso and Li [18], describes how work is distributed between drives. Link optimization followed by kinetostatic analysis, as in Kütük et al. [25], addresses geometry and loading. Neither measure alone establishes the net electrical energy saved over a complete production cycle.

Mechanism selection should therefore be accompanied by a control specification and a cycle-level power-flow model. The next section examines the complementary control functions needed for tracking, synchronization, contact regulation, and constraint handling.

4. Control Methods and Architectures

Control methods for hybrid-actuated mechanisms are organized here by functional role rather than treated as mutually exclusive alternatives. Local PID and fuzzy feedback provide axis-level regulation; adaptive, iterative-learning, and neural-network components address parameter variation and repeatable errors; predictive, robust, and optimal methods address constraints, disturbances, and performance optimization; position–force switching and compliance methods govern transitions from free motion to contact; and decentralized or energy-aware formulations describe the allocation of control authority or the selected objective. Several of these functions may therefore coexist within one press-control architecture. Joint clearance and friction are considered separately as cross-cutting physical effects because they influence tracking accuracy, actuator loading, and cycle-energy dissipation regardless of the selected controller.

Results from lightweight manipulators, prostheses, soft robots, and mobile systems are used here only to identify potentially transferable control functions, such as nonlinear approximation, adaptation, disturbance estimation, or impedance regulation. They do not establish that the same algorithms can tolerate press-scale stiffness, contact impact, forming force, actuator saturation, friction, clearance, sampling constraints, or repeated-cycle thermal loading. Transfer to press operation therefore requires press-oriented modeling, safety constraints, and experimental validation under representative loads and contact transients.

4.1. Local Feedback, Adaptive, and Learning-Based Control

Local feedback, adaptive, iterative-learning, fuzzy, and neural-network-assisted methods address different but complementary control functions. PID and Fuzzy-PID controllers primarily provide local regulation of position, velocity, current, or pressure. Adaptive control updates model or controller parameters during operation, whereas iterative-learning control uses errors from previous repetitions to improve a cyclic task. Neural networks may support nonlinear approximation, disturbance estimation, gain adaptation, or feedforward compensation. These approaches are therefore not mutually exclusive and may be combined within one layered control architecture.

PID control remains a practical choice for local tracking and regulation when the controller gains and operating range are appropriately defined. Ibrahim and Sharkawy compared an adaptive hybrid PID scheme with sliding-mode control for a flexible-joint manipulator, while other studies examined real-time PID implementation and dual-design PID controllers in robotic systems [36–38]. These results demonstrate the accessibility and low computational burden of PID control, but they do not establish general robustness outside the modeled or tested operating conditions.

Gain tuning becomes more difficult when dynamics, payload, friction, or operating speed vary. Evolutionary and genetic-algorithm-based tuning methods have been investigated for rehabilitation and soft robotic systems [39,40]. Such methods optimize performance for a selected objective and test range; they do not automatically ensure stability or robustness across the full operating envelope of a hybrid press.

Fuzzy control extends local feedback by using membership functions and rule-based nonlinear mappings. Adaptive fuzzy control, Fuzzy-PID tuning, particle-swarm optimization, and type-3 fuzzy systems have been investigated for manipulators and parallel mechanisms [41–46]. For transfer to press systems, key questions include how the rules or membership parameters are obtained, which variables are measured, and whether the controller remains stable under actuator saturation, dual-drive coupling, and changing contact loads. The complexity of the fuzzy representation alone does not establish superior industrial performance.

Adaptive and iterative-learning methods address variations and repetitive errors that fixed-gain feedback cannot always remove. Adaptive control modifies model estimates or controller parameters during operation, whereas iterative-learning control uses tracking errors from preceding cycles to improve performance in a repeated task. This distinction matters for press machinery: adaptation can address gradual changes in load, friction, or model parameters, while iterative learning is particularly relevant to repetitive stamping and forming cycles.

Adaptive control has been investigated for four-bar linkages, manipulators with friction, soft continuum manipulators, and five-bar parallel robots with uncertain dynamics [47–50]. Directly relevant hybrid-machine studies have also used adaptive and iteration-based methods for trajectory synchronization in closed-chain systems [14,15]. These results support their potential to compensate for load-dependent and repeatable tracking errors, but transfer requires examining parameter excitation, convergence, measurement noise, actuator constraints, and the stability of the coupled mechanical system.

Neural networks are best treated as learning-assisted components rather than a separate, complete control architecture. Neural networks may approximate uncertain nonlinear dynamics, estimate disturbances, adjust feedback gains, or provide feedforward compensation. Adaptive neural tracking with disturbance observers and neural-weight convergence analysis illustrates their integration with conventional feedback and adaptive structures [51,52]. Figure 3 presents a representative adaptive neural-network architecture in which the learning component estimates model uncertainty while a verified feedback structure provides the main control action.

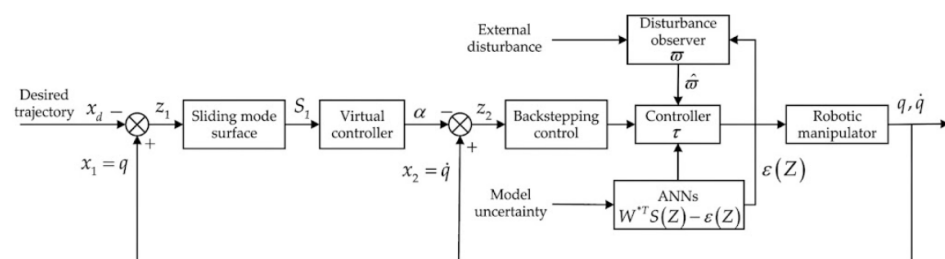


Figure 3. Adaptive neural-network tracking control architecture with a disturbance observer. (Adapted from Li et al. [51], Figure 1, under the CC BY 4.0 license. Colors and typography modified. © 2024 the original authors.).

Additional studies have combined neural networks with PID, fractional-order PID, sliding-mode control, and flexible task-space control [53–56]. Neural predictive control has also been investigated for robotic systems operating under complex nonlinear dynamics [57,58]. These studies demonstrate possible learning and approximation functions, but most concern lightweight robotic systems rather than high-stiffness press machinery. Their results therefore constitute transferable evidence and do not establish press-scale stability, energy saving, or reliability.

For forming applications, a neural component should preferably be used for bounded model correction, disturbance estimation, or feedforward compensation around a verified

local controller. Evaluation should report the training range, update rule, stability assumptions, behavior outside the learned region, actuator saturation, and computational time. A reduction in tracking error should not automatically be interpreted as a reduction in cycle energy.

For hybrid-actuated presses, the most defensible implementation is a layered structure in which a conventional local feedback loop provides verified axis regulation, while fuzzy tuning, adaptive estimation, iterative learning, or neural approximation is introduced only for a clearly identified uncertainty or repeatable error. The benefit of the additional component should be demonstrated under representative press-scale stiffness, contact transients, forming loads, actuator saturation, joint clearance, friction, and thermal conditions. These methods can improve tracking or disturbance compensation, but such improvements do not by themselves establish lower electrical energy consumption.

4.2. Predictive, Robust, and Optimal Control

Predictive, robust, and optimal-control methods address different but complementary requirements. Model Predictive Control (MPC) coordinates future system behavior while explicitly considering actuator and process constraints. Sliding-mode and disturbance-observer-based methods focus on robustness to uncertain dynamics and rapidly varying external loads. Optimal control and trajectory planning define a task-specific objective, such as cycle time, energy, tracking accuracy, or actuator effort. These approaches should therefore be compared by functional role rather than treated as directly interchangeable controllers.

MPC repeatedly solves a finite-horizon optimization problem using a prediction model of the controlled system. The formulation can include coupled state variables, input limits, trajectory requirements, force constraints, and selected performance objectives. Studies of cable-driven parallel robots, running bipeds, collaborative manipulators, and parallel mechanisms illustrate its application to multivariable systems with dynamic and operational constraints [59–62]. These studies provide evidence of the general capabilities of MPC, but their mechanical stiffness, loads, sampling rates, and interaction conditions differ from those of industrial presses.

Optimization-based MPC design and coordinated trajectory planning have also been investigated for robotic manipulators [63,64]. Predictive interaction control extends the formulation to systems in which contact forces and environmental interaction must be considered [65]. For press applications, this requires a prediction model that represents not only free ram motion but also tool–workpiece contact, forming-force development, actuator saturation, and the transition between operating phases. A model that is adequate during approach may not retain the same accuracy during heavy forming contact.

Real-time nonlinear MPC and approximate time-optimal MPC demonstrate possible routes to online implementation [66,67]. However, real-time feasibility cannot be inferred solely from a fast solver or average computation time. The worst-case optimization time, state-estimation delay, communication delay, sampling interval, model evaluation, and safety logic must all remain within the available control period. This requirement becomes particularly important in high-rate stamping and multi-axis press systems.

A claim of real-time MPC suitability should report the worst-case, not just the average, solution time and include state estimation, model evaluation, communication, constraint handling, safety logic, and solver execution. All of these operations must remain within the available sampling period. For high-speed or multi-axis presses, fast local current, velocity, position, pressure, or force loops can operate at the actuator rate, while MPC updates trajectories, constraints, operating modes, or energy references at a slower supervisory rate.

Hybrid MPC has been applied directly to servo-press control [68], while enhanced MPC has been investigated for the pressure-building phase of a pump-controlled hydraulic

die cushion [69]. Robust MPC combined with proportional–integral force control has also been studied for an electrohydraulic system with a compressive elastic load [70]. These studies provide closer application evidence than general robotic examples, although they represent different subsystems and validation conditions.

Sliding-mode control and disturbance observers address a different control function. Sliding-mode methods drive the system toward a selected manifold and can provide robustness when uncertainty and disturbance bounds satisfy the controller-design assumptions. Disturbance observers estimate unmodeled loads or dynamics and may be combined with conventional, adaptive, predictive, or sliding-mode feedback. Studies of manipulators, flexible-link systems, cable-driven parallel robots, and mobile parallel platforms illustrate these approaches [71–78].

The theoretical robustness of sliding-mode control does not remove practical implementation limitations. Classical switching laws may introduce chattering, which can excite unmodeled structural dynamics, increase actuator activity, and contribute to mechanical wear. Measurement noise, discrete sampling, observer bandwidth, actuator saturation, and time delay can also affect performance. Boundary-layer, continuous, higher-order, or observer-assisted implementations can reduce some of these effects, but their benefits must be evaluated under the target system’s actual load and bandwidth conditions.

For press machinery, robust control is especially relevant during tool–workpiece contact, friction variation, pressure development, and rapid forming-load changes. Nevertheless, most of the reviewed sliding-mode studies concern robotic systems rather than full-scale presses. Their findings therefore support selecting disturbance-rejection principles but do not directly establish press-scale tracking performance, force accuracy, thermal duty, or energy savings. Press transfer requires testing under high structural stiffness, representative contact transients, actuator limits, joint clearance, and friction.

Optimal control and trajectory planning define a performance objective subject to dynamic and operational constraints. Energy-optimal impedance control, minimum-time manipulation, smooth time-optimal planning, and evolutionary trajectory optimization illustrate different formulations [79–82]. These objectives are not equivalent. A time-optimal trajectory may increase peak torque, peak electrical power, vibration, or braking demand, whereas an energy-oriented trajectory may increase cycle time. Consequently, an “optimal” result is meaningful only together with its cost function, weighting factors, model, constraints, and reference case.

Nonlinear optimal control of cable-driven robots and automated motion optimization of a nine-bar linkage provide additional examples of dynamic and mechanism-level optimization [83,84]. Other studies consider time-optimal planning and min–max control in the presence of uncertainty or sensor faults [85,86]. For hybrid-actuated presses, relevant optimization variables may include the two input trajectories, cycle time, forming velocity, peak and root-mean-square actuator torque, force-tracking error, energy per cycle, and storage state. Link dimensions may also be included when mechanism synthesis and control design are performed jointly.

These methods are therefore complementary in practice. MPC is most appropriate when coupled variables and explicit constraints require coordination. Sliding-mode and disturbance-observer methods can support fast rejection of bounded disturbances and load variation. Optimal-control and trajectory-planning methods define offline or online trade-offs among productivity, motion accuracy, actuator loading, and energy. A hybrid press may combine an optimized reference trajectory, supervisory MPC, and robust local feedback rather than relying on only one approach.

The reviewed studies do not provide a universal performance ranking because they use different mechanisms, loads, sampling intervals, constraints, objectives, and validation

procedures. A fair comparison should use the same mechanism, forming task, trajectory, actuator limits, contact model, computational platform, and performance indicators. The evaluation should include trajectory and force errors, worst-case computation time, peak and root-mean-square torque, actuator saturation, cycle time, thermal duty, and net electrical energy over a complete steady production cycle.

4.3. Contact Regulation, Compliance, and Mode Switching

The dominant control objective changes as a press moves through free motion, initial tool–workpiece contact, forming, dwell or low-speed motion, and return. Position and velocity tracking generally dominate during approach and return, whereas force or pressure regulation becomes more important after contact. Consequently, in this context, hybrid control refers to coordinating or switching control functions and should not be confused with the press’s hybrid mechanical actuation architecture.

Combined controllers have been investigated in flexible manipulators, soft robotic systems, Stewart platforms, underwater vehicle–manipulator systems, and pneumatic or compliant robots [87–96]. These studies illustrate the integration of feedback, learning, robust compensation, and switching logic. However, their stiffness, force levels, actuator dynamics, and contact conditions differ substantially from those of metal-forming machinery. They therefore provide transferable control concepts rather than direct evidence of press-scale performance.

For press applications, the most important transition occurs between free ram motion and workpiece contact. During approach, the controller must track the prescribed position and velocity while respecting actuator-speed and stroke constraints. After contact, the control objective shifts toward forming-force, pressure, or low-speed regulation. A practical implementation therefore requires a contact-detection mechanism and a coordinated transfer of authority from the motion controller to the force or pressure controller.

Contact may be detected through a force or pressure threshold, a position or velocity residual, or a model-based estimate. A single threshold without filtering or hysteresis may cause repeated switching with vibration, clearance, friction, or measurement noise. Contact detection should therefore be designed together with the sensing bandwidth, filtering, actuator dynamics, and expected forming-load development. The selected criterion should also distinguish actual workpiece contact from backlash take-up, mechanical impact, or transient hydraulic pressure.

An instantaneous hard switch between independently tuned motion and force controllers may introduce discontinuities in torque, motor current, valve command, pressure reference, or integral states. A practical transition should use filtered or model-based contact detection, hysteresis, ramped force or pressure references, bumpless transfer of controller states, anti-windup, command-continuity constraints, and, where appropriate, a finite blending interval. Stability and bounded transition behavior should be verified under representative contact stiffness, clearance, friction, measurement noise, actuator saturation, and forming-load variation.

Presses and related hydraulic axes provide the closest evidence for this control problem. Enhanced MPC with disturbance compensation has been studied for the pressure-building phase of a pump-controlled hydraulic die cushion [69]. Bilateral motion and force control has also been investigated for a servo die-cushion system [97]. These studies show that phase-dependent control can coordinate motion and load variables, but their conclusions remain specific to the modeled or tested subsystem.

Angle–force control of electrohydraulic leveling systems and hybrid position–force control of electrohydraulic servo-actuators provide further examples of coupled motion and load regulation [98,99]. Figure 4 illustrates a representative architecture in which a

switching signal coordinates position and force controllers. The figure should be interpreted as a mode-coordination principle rather than as a universal press controller.

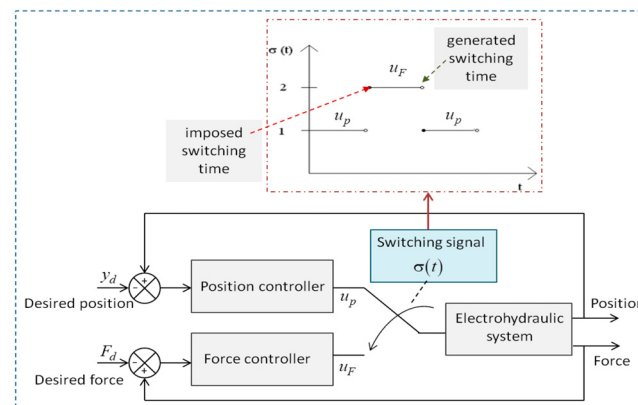


Figure 4. Hybrid position–force control of an electrohydraulic servo-actuator. (Adapted from Sidhom et al. [99], Figure 2, under the CC BY 4.0 license. Colors and typography modified. © 2022 the original authors.).

Position–force switching for hydraulic actuators and a sliding-mode/PID combination for an electrohydraulic servo-actuator provide additional examples [100,101]. Hybrid force and position control has also been studied for electromechanical feed axes [102], while adaptive integral robust control has been developed for pump-controlled hydraulic presses [103]. The latter is a robust and adaptive hydraulic-control method rather than a model-predictive controller, and its contribution should be described accordingly.

Hybrid MPC has been applied to servo-press control [68], and robust MPC combined with proportional–integral force control has been studied for an electrohydraulic system with a compressive elastic load [70]. These approaches can coordinate constraints, references, and operating modes, but their suitability depends on prediction-model accuracy, sampling rate, optimization time, and the dynamic properties of the controlled axis. Array digital valves introduce an additional discrete switching problem in electrohydraulic pressure regulation [104].

Compliance and passivity address the interaction problem from a different perspective. Passivity-based control constrains the energy exchanged between the controlled system and its environment. It may use active actuators and powered feedback and is therefore distinct from a purely passive mechanical element or a passive energy-saving device. Studies of space manipulators, aerial manipulation, and multi-agent systems illustrate passivity-based coordination and interaction stability [105,106].

Mechanical or controlled compliance can reduce the severity of contact transients and accommodate limited position uncertainty. Passive-compliance control and hybrid parallel compliance have been investigated for aerial and robotic systems [107,108]. Deflection-domain passivity methods extend this concept to variable-stiffness systems and rotational motion [109,110], while variable-impedance and fractal-impedance controllers provide alternative interaction frameworks [111,112].

For forming machinery, compliance should be introduced cautiously. Excessive structural compliance can reduce positional repeatability, alter the force–displacement relationship, increase tool deflection, and conflict with the high stiffness required for accurate material deformation. Compliance may therefore be most useful as a bounded local, actuator, or virtual-control property rather than as a reduction in the press frame’s global stiffness or primary load path. Evidence from compliant joints in legged systems [113] supports general interaction principles but does not establish suitability for high-load pressing.

Passivity or compliance also does not by itself demonstrate lower electrical energy consumption. A compliant element may store and return some reversible mechanical energy, but damping, deformation, active stiffness adjustment, and controller action can introduce additional losses. Evaluation should therefore distinguish interaction stability, peak contact force, position error, stored mechanical energy, dissipated energy, and net electrical energy.

For a hybrid-actuated press, a defensible phase-dependent architecture may use local position control during approach and return, contact detection with hysteresis or filtering, a continuous transition toward force or pressure regulation, and supervisory enforcement of actuator and process constraints. Passivity or impedance concepts may support the transition where interaction uncertainty justifies them. The complete architecture should be tested during free motion, initial contact, sustained forming, dwell or low-speed operation, release, return, and off-nominal loading.

The evaluation should report trajectory error before contact, contact-detection delay, peak impact force, force or pressure error after contact, switching transient, commanded-input continuity, actuator saturation, closed-loop stability, and computational demand. When energy performance is claimed, also measure peak torque, root-mean-square torque, thermal duty, and net energy over the complete cycle. Smooth mode coordination can improve tracking and reduce undesirable transients, but these effects should not automatically be reported as cycle-level energy savings.

4.4. Decentralized and Energy-Aware Control Architectures

Decentralized and energy-aware control describe different aspects of a control system. Decentralized control concerns allocating local control authority among actuators or subsystems, whereas distributed control also requires information exchange and coordination among those local controllers. Energy-aware control defines an objective or evaluation criterion, such as actuator work, electrical energy, peak power, or storage state. These concepts are not mutually exclusive: a decentralized architecture may contain energy-aware local controllers, while a centralized or hierarchical architecture may also optimize energy-related objectives.

Decentralized adaptive control has been investigated for collaborative manipulation and uncertain networked manipulators [114,115]. Event-triggered communication and distributed optimal control provide further examples of coordinating local subsystems while limiting communication or allocating shared objectives [116,117]. These studies demonstrate the potential advantages of modularity, parallel computation, and local autonomy, but their multi-robot context differs from a mechanically closed hybrid linkage.

For a two-input hybrid mechanism, the relevant issue is not the number of agents but the preservation of coordinated motion through a shared mechanical chain. The main-drive and servo-drive controllers may be implemented as separate local loops, but they must maintain a common phase reference, compatible actuator limits, and the required output trajectory. A small synchronization error between the inputs can produce output-position error, internal constraint forces, or additional corrective torque, particularly near poorly conditioned configurations.

Independent tuning of local controllers does not guarantee acceptable behavior of the complete mechanism. Coupling through the linkage means that the action of one actuator changes the load seen by the other. A decentralized implementation should therefore account for cross-axis interaction, shared kinematic constraints, and potential actuator saturation. Where the coupling is strong, local controllers may require a supervisory coordination layer or exchange of estimated position, velocity, torque, and constraint information.

Decentralized adaptive control of high-degree-of-freedom manipulators and passivity-based multi-robot control with communication delays illustrate the influence of model uncertainty and information exchange on coordinated motion [118,119]. Distributed actuation in segmented soft robots and adaptive-impedance control of modular manipulators extend these concepts to mechanically distributed systems [120,121]. These studies provide transferable architectural principles, but they do not directly establish tracking accuracy, internal loading, or reliability for high-stiffness press mechanisms.

Communication and computation delays require particular attention. In a closed-chain hybrid linkage, delayed information can create phase mismatch between the inputs even when each local axis remains stable in isolation. Event-triggered communication may reduce data transfer, but excessively sparse updates can degrade trajectory coordination. Evaluation should therefore include communication latency, update frequency, synchronization error, output tracking error, and the stability of the complete coupled system rather than only the performance of individual local loops.

Energy-aware control addresses a separate question: whether energy, power, or actuator effort is included explicitly in the controller objective or measured as an outcome. An energy-related term may be incorporated into PID tuning, optimal control, MPC, trajectory planning, or supervisory logic. The presence of such a term does not by itself guarantee a reduction in net electrical energy, because improvements in one indicator may be accompanied by increased losses, longer cycle time, or additional computational and actuator activity.

Observer-assisted control of a compliant manipulator has been evaluated using an actuator-energy measure derived from joint torque and angular velocity [122]. The reported reductions were obtained for a specific manipulator, stiffness condition, motion, and set of reference controllers. They demonstrate that control design can influence calculated actuator work, but they constitute transferable evidence rather than direct press-scale validation.

Reviews of industrial robotic energy consumption further show that reported values depend strongly on the selected system boundary, trajectory, payload, standby condition, and auxiliary equipment [123]. Energy-optimal gait selection and comparisons of PID and MPC in industrial robots examine other application-specific objectives [124,125]. Their relevance to presses lies in the formulation of trade-offs among tracking performance, cycle time, actuator effort, and energy rather than in the direct transfer of reported percentage savings.

Adaptive sliding-mode control of a hybrid kinematic robot provides additional evidence for tracking under variable conditions [126]. However, improved tracking or adaptive gain selection should not be interpreted as an energy benefit unless energy or electrical input is explicitly calculated or measured. A controller may reduce position error while increasing switching activity, root-mean-square torque, current demand, or thermal loading.

For hybrid-actuated presses, energy-aware control should distinguish among several possible objectives. Minimizing peak motor torque may reduce the required actuator rating but may not reduce energy per cycle. Minimizing peak grid power may shift demand to a flywheel, capacitor, or hydraulic accumulator while introducing storage losses. Minimizing mechanical actuator work does not necessarily minimize electrical input because drive, converter, transmission, hydraulic, and auxiliary losses remain. These quantities should therefore be reported separately.

Energy objectives should also reflect the phase structure of the press cycle. During approach and return, the controller may prioritize trajectory tracking and cycle time. During forming, force or pressure accuracy and actuator limits become dominant. During deceleration, negative mechanical power may become available for regeneration. During dwell or low-speed motion, output mechanical power may be small while holding torque, hydraulic pressure, or drive losses remain nonzero. A single energy weighting applied uniformly over the entire cycle may therefore fail to represent the physical role of each phase.

A practical architecture may combine decentralized local regulation with hierarchical energy supervision. Fast local controllers can regulate the main motor, servomotor, hydraulic axis, or die cushion, while a slower supervisory layer coordinates the phase reference, trajectory, actuator limits, storage state, and energy-recovery opportunities. This structure lets local loops keep the sampling rates needed for motion and force control without requiring the full energy-management optimization to run at the same frequency.

The benefit of decentralized or energy-aware control should be evaluated at the level of the complete machine. Relevant control indicators include synchronization error between the inputs, trajectory and force error, communication delay, constraint violations, actuator saturation, and worst-case computation time. Relevant energy indicators include peak and root-mean-square torque, peak electrical power, mechanical work of each actuator, storage losses, auxiliary consumption, thermal duty, and net electrical energy per completed steady production cycle.

Storage-based comparisons must also preserve the initial and final energy states of the storage device. Otherwise, a controller may appear to reduce input energy by discharging a pre-charged flywheel, capacitor, battery, or hydraulic accumulator during the evaluated cycles. A valid steady-cycle comparison should either restore the initial storage state or include the change in stored energy in the reported balance.

Accordingly, decentralized and energy-aware approaches should not be treated as separate competing controller families. Decentralization determines where decisions are made and how information is exchanged, whereas energy awareness determines which performance quantities are included in the control objective or evaluation. Their suitability for a hybrid press depends on whether they preserve global synchronization, satisfy mechanical and process constraints, and demonstrate measurable benefits within a clearly defined machine-level energy boundary.

4.5. Effects of Joint Clearance and Friction on Tracking and Energy Flow

Joint clearance and friction are cross-cutting physical nonidealities that affect all control methods considered in the preceding sections. They should not be treated only as unmodeled disturbances, because they directly influence mechanism kinematics, actuator loading, contact behavior, and irreversible energy dissipation. Their effects become particularly important in closed-chain hybrid mechanisms, where two coordinated inputs act through the same mechanical structure.

Clearance in revolute joints, slider guides, and transmission elements introduces backlash, dead zones, intermittent contact, and impact loading. In a two-input linkage, clearance can change the instantaneous relationship between the actuator coordinates and the output motion. Consequently, tracking the main motor and servomotor individually does not necessarily ensure accurate ram motion when joint contact states change. Dynamic studies of high-speed press mechanisms and hybrid multi-link systems show that clearance can modify the response, increase vibration, and reduce motion accuracy [8,23,24].

The influence of clearance depends on mechanism configuration and operating phase. During rapid approach and return, backlash take-up can produce transient output errors and impacts. During forming, high joint and guide forces can shift the contact state within the clearance and alter load transmission. Near a singular or poorly conditioned configuration, a relatively small input or joint displacement error may produce a larger output error or a substantial increase in internal reactions. Clearance should therefore be considered together with transmission quality, input synchronization, and forming load.

Synchronization error and clearance may also reinforce one another. A phase difference between the two actuators changes the closed-chain configuration and constraint forces. If the mechanism contains clearances, the phase error may cause repeated separation and

impact between joint surfaces, increasing vibration, peak contact force, corrective servo torque, and wear. The resulting internal mechanical stress cannot be evaluated from output trajectory error alone; it requires a dynamic model that includes joint contact, structural compliance, and constraint reactions.

Friction introduces a different but related set of effects. Coulomb friction, viscous friction, seal friction, guide friction, and velocity-dependent effects such as the Stribeck region can produce tracking error, hysteresis, stick–slip motion, heat generation, and additional actuator effort. Friction varies with velocity, normal load, lubrication, temperature, surface condition, and wear. A friction model identified under unloaded motion may therefore be inadequate during high-force forming.

Adaptive control, disturbance observers, and friction-compensation methods may reduce the tracking error associated with uncertain friction [48]. However, control compensation does not eliminate the physical energy dissipated at the joint, guide, seal, or transmission interface. A controller can maintain the prescribed trajectory by supplying additional torque, but this may increase motor current, root-mean-square torque, converter losses, and thermal duty. Improved tracking should therefore not automatically be interpreted as improved energy efficiency.

Clearance and friction also influence transitions between free motion and workpiece contact. Backlash take-up or a frictional force reversal may resemble the onset of tool–workpiece contact in measured force, pressure, or motor-current signals. This can cause premature or repeated switching between position and force control. Contact detection should therefore include appropriate filtering, hysteresis, or model-based residuals, and the switching logic should be tested under representative clearance, friction, load, and velocity conditions.

The energy effect of these nonidealities should be evaluated over the complete cycle. Clearance impacts may increase vibration and peak actuator demand, while friction produces irreversible loss during approach, forming, dwell, and return. During dwell or low-speed operation, output mechanical power may be small even though friction, holding torque, hydraulic pressure maintenance, and electrical losses remain nonzero. During return, friction reduces the mechanical energy otherwise available for regeneration.

Press-oriented studies should report the assumed or measured joint and guide clearances, contact or impact model, friction law, parameter-identification method, lubrication condition, and relevant temperature range. The evaluation should include ram trajectory error, phase error between the two actuator inputs, force or pressure error, peak and root-mean-square servo torque, impact forces, cycle energy, thermal duty, vibration, and wear-related changes. When numerical models are used, report sensitivity to clearance and friction parameters rather than presenting only one nominal condition.

Accordingly, joint clearance and friction should be incorporated into mechanism synthesis, actuator sizing, controller tuning, and energy accounting. A control method that performs well for an ideal-joint model may require substantially different gains, robustness margins, or actuator capacity when mechanical nonidealities are included. Considering these factors therefore provides an important link between the nominal control strategies reviewed above and their practical implementation in industrial press systems.

4.6. Comparative Synthesis of Control Functions

Table 3 organizes the reviewed control approaches by functional role rather than treating them as mutually exclusive algorithm families. Local feedback provides axis-level regulation; adaptive, iterative-learning, fuzzy, and neural-network components address parameter variation, repeatable errors, and nonlinear compensation; robust and predictive methods address disturbances and constraints; mode-switching and compliance methods

govern physical interaction; and decentralized or energy-aware formulations describe control allocation or optimization objectives. Several of these functions may coexist within one press-control architecture.

Table 3. Functional comparison of control approaches for hybrid-actuated linkage and press systems.

Control Function	Candidate Methods and Role	Main Evaluation Issues	Evidence Context
Local regulation	PID or fuzzy PID for axis tracking and pressure regulation.	Tuning, operating range, saturation, coupling, friction sensitivity, and backlash.	Manipulator studies [36,43,45,46].
Adaptation and learning	Parameter updates and cycle-to-cycle tracking correction.	Convergence assumptions, excitation, repeated disturbances, noise, parameter drift, and friction compensation.	Hybrid and five-bar systems [14,15]; adjacent robotics [47,48].
Disturbance rejection	Sliding-mode control and disturbance observers.	Chattering, uncertainty bounds, clearance impacts, friction variation, measurement quality, and bandwidth.	Robotic and hydraulic axes [71,73,74,101].
Prediction and constraints	MPC for coupled variables and explicit limits.	Model fidelity, clearance and friction representation, worst-case optimization time, and constraint feasibility.	Robots, servo press, and die cushion [62,68,69].
Nonlinear compensation	Neural approximation, adaptive gains, or learned feedforward.	Training coverage, stability assumptions, and extrapolation.	Predominantly robotic applications [51,53–55].
Mode coordination	Position/force or position/pressure switching.	Contact detection, backlash take-up, friction reversal, bumpless transfer, transition continuity, and stability.	Die cushions, hydraulic actuators, and feed axes [97,99,100,102].
Interaction properties	Passivity, impedance, and compliance.	Interaction stability, required structural stiffness, dissipated energy, and distinction from electrical energy saving.	Robotic and variable-stiffness systems [106,109–111].
Distributed authority	Local controllers with coordinated information exchange.	Global synchronization, communication delay, mechanical coupling, internal reactions, and shared constraints.	Cooperative or modular robots [114,115,121].
Explicit optimization	Time, energy, tracking, or actuator-effort objectives.	Objective definition, constraints, and baseline comparability.	Robotic and linkage studies [79,80,84,85].
Integrated architecture	Combine the functions justified by the process.	End-to-end validation and integration cost.	Authors' synthesis; no universal benchmark ranking.

Joint clearance and friction are not separate controller categories. As discussed in Section 4.5, they are cross-cutting physical effects that influence local tracking, adaptation, disturbance rejection, prediction-model accuracy, contact detection, mode switching, actuator loading, and energy consumption. Controller comparison should therefore retain the mechanical assumptions under which each method was modeled or tested.

The dominant control requirement changes through the press cycle. Approach and return emphasize position and velocity tracking. Initial contact introduces impact and contact-detection requirements. Forming emphasizes force or pressure regulation together

with actuator and process constraints. Dwell or low-speed operation may require sustained torque or pressure despite small output velocity. Deceleration and return may additionally create conditions for regenerative operation. The control architecture should coordinate these phases without introducing discontinuities or violating actuator limits.

Direct studies of hybrid machines, servo presses, hydraulic presses, and die-cushion systems provide a closer basis for press design than robotic applications with substantially different stiffness, load, and duty conditions [14,15,68,69,97,103]. Nevertheless, even within this closer evidence group, a numerical mechanism model, an experiment on one actuator or hydraulic subsystem, and a full-machine test represent different validation levels.

A candidate control architecture should be selected based on the functions required by the process rather than an assumed hierarchy of algorithm sophistication. A repetitive operation with limited variation may be adequately controlled using local feedback supplemented by iterative-learning compensation. A multi-axis press with explicit trajectory, force, actuator, and storage constraints may justify supervisory MPC and coordinated mode switching. Robust or learning-assisted components should be introduced only when the corresponding disturbance, uncertainty, or repetitive error has been identified.

The additional complexity must be supported by measurable improvement under representative operating conditions. Evaluation should include tracking and force errors, contact-transition behavior, phase synchronization, clearance and friction sensitivity, worst-case computation time, actuator saturation, peak and root-mean-square torque, thermal duty, and net electrical energy over a complete steady cycle. Because control also determines when power is supplied, dissipated, absorbed, or returned, the following section examines energy recovery, storage, hydraulic loss reduction, and passive demand shaping in relation to the operating cycle.

5. Energy Management in Cyclic Machinery

Energy management in a cyclic machine involves reducing losses, shaping demand, recovering available negative power, and buffering the mismatch between supply and load. These functions are physically different. A lower peak motor rating does not necessarily mean lower energy use, and adding storage can introduce losses even when it reduces peak demand.

The relevant boundary may include motors, drives, transmission, hydraulics, cooling, storage, and auxiliary equipment. Mechanical or electrical energy recovered within this boundary should be distinguished from energy exported outside it. Comparisons should use the same production task and define how idle operation and auxiliary loads are included.

The following subsections separate electrical regeneration, hybrid electrical storage, hydraulic energy management, flywheels, vibration harvesting, and passive mechanical measures. Evidence from vehicles and robotics is retained as context, while press-specific implications are evaluated separately.

5.1. Electrical Regeneration

An electric drive can return mechanical energy when it operates in a generating regime. The returned energy may feed another axis, charge storage, return to the grid, or be dissipated if no receiving path is available. Reviews of vehicle regenerative braking explain torque allocation and storage constraints [127,128]. Anti-lock braking coordination is vehicle-specific and should not be presented as a general requirement of multi-axis presses.

MPC and other optimization methods have been studied for vehicle brake blending and energy recovery [129,130]. For a press, the transferable concept is coordinated control of negative power under electrical and mechanical limits. Vehicle stopping-distance and tire-adhesion constraints do not directly describe the press problem.

Recovery is limited by motor and converter operation, the available receiving load, and storage acceptance [131,132]. Low speed, high state of charge, and voltage or current limits may reduce recoverable energy. The recoverable mechanical energy and the net useful electrical energy should be reported separately.

Fuzzy/optimization methods coordinated regenerative/anti-lock braking, and broader vehicle reviews show the range of proposed strategies [133–136]. They motivate power-flow coordination, but their numerical savings are not transferred to presses without a representative press-cycle model and validation.

5.2. Battery–Supercapacitor Hybrid Storage

Battery–supercapacitor hybrid energy storage combines an energy-oriented storage medium with a device suited to short power transients. The reviewed systems commonly connect the devices through converters and a shared electrical bus. Vehicle-focused reviews describe the available topologies and control approaches [137–139].

A supercapacitor can absorb or supply transient power and thereby change battery current demand. The benefit depends on storage sizing, converter losses, operating limits, and control. Peak smoothing or reduced battery stress should not be reported as a measured reduction in total machine energy unless that outcome was evaluated [140,141].

A hybrid store adds hardware, control states, and loss mechanisms. Energy-management decisions must account for the state of charge or energy of each device and preserve capacity for the next regenerative event. These requirements may be worthwhile for some duty cycles, but batteries are not automatically necessary in a grid-connected press with other power-receiving options.

Energy-storage surveys distinguish technologies by power capability, energy capacity, response, and lifetime [140]. A battery–supercapacitor combination is one member of this broader design space; it should not be used as a synonym for all hybrid storage arrangements.

Figure 5 summarizes hybrid-storage combinations reviewed for renewable-energy integration [142]. It is a qualitative classification from that application context, rather than a press-specific design chart or a measured ranking of press efficiency.

Technology	Lithium-Ion	Supercapacitors	Flywheels	Flow Batteries	CAES	TES	Hydrogen	SMES	Pumped Hydro
Lithium-Ion	—	High	High	Moderate	Low	Low	High	High	Moderate
Supercapacitors	High	—	High	Moderate	Low	Low	Moderate	High	Low
Flywheels	High	High	—	Moderate	Low	Low	Moderate	High	Low
Flow Batteries	Moderate	Moderate	Moderate	—	High	Moderate	High	Moderate	High
CAES	Low	Low	Low	High	—	High	High	Low	High
TES	Low	Low	Low	Moderate	High	—	High	Low	High
Hydrogen	High	Moderate	Moderate	High	High	High	—	High	High
SMES	High	High	High	Moderate	Low	Low	High	—	High
Pumped Hydro	Moderate	Low	Low	High	High	High	High	High	—

Figure 5. Qualitative comparison of hybrid energy-storage combinations in a renewable-energy context. (Adapted from Adeyinka et al. [142], Figure 3, under the CC BY 4.0 license. Color scale and layout modified. © 2024 the original authors.).

Reviews of supercapacitors and hybrid supplies for electric drives provide additional context for transient buffering [143,144]. Their relevance to presses depends on the actual power-time profile, acceptable bus-voltage variation, and the losses of the complete storage path.

Press evaluation should compare a proposed hybrid store with alternatives such as a shared DC bus, capacitive buffering, line regeneration, or mechanical storage. The

comparison should include useful recovered energy, peak grid power, standby losses, thermal duty, and life-cycle operating requirements.

5.3. Hydraulic Storage and Loss Reduction

Hydraulic accumulators store pressure energy and can buffer demand or recover energy from an overrunning load. Efficient circuit architectures, including pump-controlled actuation and independent metering, address a different function: reducing avoidable hydraulic losses. These functions may be combined, but an accumulator does not itself guarantee energy recovery [145,146].

Accumulator-assisted systems can exchange power rapidly, while the usable energy depends on pressure limits, pre-charge, volume, and thermodynamic behavior. Excavator-boom recovery and hydraulic-press system studies illustrate different applications [147,148]. Excavator results should retain their original load and motion context.

Hydraulic energy management involves pressure losses, leakage, thermal effects, and dynamic constraints. Circuit-level analyses and alternative storage concepts illustrate continuing design development [148,149]. A storage technology's nominal capacity should be distinguished from the energy recoverable in a loaded production cycle.

Energy-regenerating electrohydraulic actuators and systematic management of hydraulic servo axes provide closer subsystem evidence [150,151]. Reviews of hydraulic energy saving also identify the importance of matching supply and load [152]. System-level performance remains dependent on the circuit and duty cycle.

For a press or die cushion, an accumulator may buffer a short demand peak, support a pressure stage, or receive energy during a suitable return phase. Whether it lowers net input energy depends on the charging path, reuse opportunities, and losses. Therefore, peak pump power, recovered energy, and total cycle consumption should be reported separately [152–154].

5.4. Flywheel Energy Storage

A flywheel stores kinetic energy and exchanges it with the drive as speed changes. Conventional press flywheels and motor–generator flywheel storage systems use this principle in different architectures. Reviews describe their mechanical and electrical design options [155,156]; Figure 6 shows a general storage-system configuration.

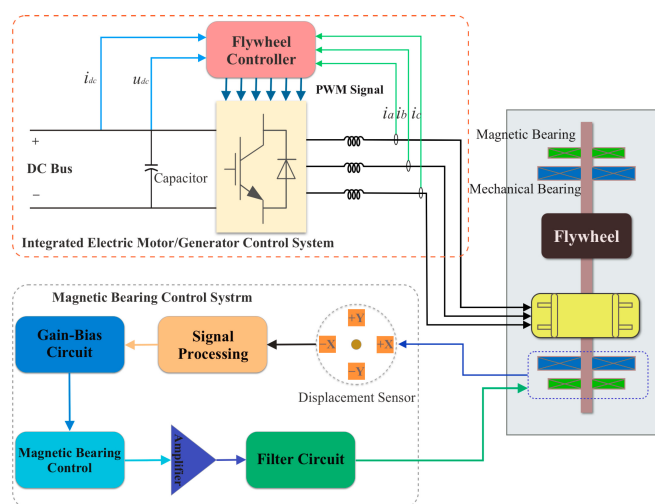


Figure 6. Architecture of a flywheel energy-storage system and its motor/generator and magnetic-bearing control subsystems. (Adapted from Xu et al. [156], Figure 3, under the CC BY 4.0 license. Graphical presentation modified. © 2023 the original authors.).

Flywheels can buffer short power peaks and repeated cyclic demand. Rotor design, bearings, windage, allowable speed range, and transmission losses determine usable performance [157]. A lower peak input-power requirement should not be confused with reduced forming work or reduced net electrical energy.

A flywheel-assisted servo press provides direct evidence of mechanical energy sharing during blanking [18]. Its reported stamping-energy distribution cannot be generalized to a complete plant or to every motion profile. Press-specific evaluation should retain flywheel speed variation, inertia, forming work, and the servo contribution.

Flywheel storage also introduces standby losses, mass, and rotational-energy containment requirements [158]. The appropriate comparison is between complete drive configurations performing the same task, rather than storage devices compared only by nominal power density.

Motor-generator design and developments in flywheel technology can inform storage selection [159,160]. Their relevance to an industrial press must be assessed against the required response, speed range, integration method, and operating schedule.

Renewable-energy studies provide further examples of flywheel buffering and electrical-machine design [161,162]. They support the general storage principle, but renewable intermittency and press loading are different duty cycles.

5.5. *Vibration Harvesting and Regenerative Suspension*

Vibration harvesting converts oscillatory motion into useful electrical energy. Regenerative vehicle suspension and low-power vibration harvesters operate at different scales and should be distinguished. In presses, harvesting is most plausible for auxiliary sensing unless a measured power balance shows a meaningful contribution to the main drive.

The reviewed suspension and vibration-harvesting studies do not demonstrate press-scale main-drive savings. Their most defensible press application is supplying wireless sensors, local monitoring electronics, or small diagnostic storage. Any claim of a meaningful contribution to the press drive would require measured harvested electrical energy, conversion and storage losses, the production duty cycle, auxiliary-load demand, and the influence of the harvester on machine vibration and dynamics.

Transduction options include electromagnetic and piezoelectric devices, with tuning or frequency-conversion methods used to match the available excitation [163–165]. Output depends on vibration amplitude, spectrum, mounting, electrical load, and conversion losses. Continuous sensor operation cannot be assumed without an energy budget.

A harvester also changes the mechanical loading from which it extracts energy. Performance should therefore include both useful electrical output and any effect on the machine. Durability, intermittent excitation, and storage for low-vibration intervals matter when the purpose is condition monitoring.

Automotive studies investigate regenerative shock absorbers and electromagnetic suspension systems [166,167]. These provide relevant transduction and control concepts, but do not directly quantify recoverable energy in a forging or stamping press.

Reviews of bridge vibration harvesting and regenerative shock absorbers cover different excitation sources and objectives [168,169]. Their results should be presented as application-specific evidence rather than industrial-press efficiency improvements.

For a press-mounted sensor, an appropriate validation would report harvested energy over representative production and idle periods, sensor consumption, storage losses, and data availability. Frequency-tuning and up-conversion concepts may help match the source, but must be evaluated under the actual vibration spectrum [163–165].

Broader reviews of regenerative suspension and vehicle energy-recovery systems place harvesting among several auxiliary recovery paths [170,171]. They do not justify treating vibration energy as a substantial fraction of the main forming-energy demand.

5.6. Passive Mechanics and Demand Shaping

Springs, counterweights, and balancing linkages can redistribute torque and store or return mechanical energy during a cycle. Gravity-compensation studies illustrate these effects [172–174]. In an ideal lossless closed cycle, balancing does not remove the work required for irreversible material deformation. Its benefit may arise through reduced actuator effort, lower losses, or more favorable power demand.

Passive components introduce their own mass, geometry, and tuning requirements. Their performance can change with payload or motion profile. Variable-stiffness mechanisms may require powered adjustment, so the energy needed to change stiffness should be included when evaluating overall consumption.

Evaluate passive balancing using several simultaneous indicators. A reduction in motor torque may be accompanied by increased moving mass, shaking force, shaking moment, bearing load, structural vibration, or adjustment work. For an adjustable or variable-stiffness compensator, the energy required to change stiffness, geometry, or preload should be included in the cycle balance. A beneficial design should reduce the targeted actuator or loss metric without introducing an unacceptable dynamic, structural, or maintenance penalty.

Gear–spring gravity compensation and statically balanced spatial mechanisms show how to match a balancing law to the load [172,174,175]. These methods inform mechanism design but require a separate assessment for press loading and stroke requirements.

Variable-stiffness actuator studies address ways of changing mechanical compliance [176–178]. Adjustable compliance can be useful for interaction or energy exchange, but is not equivalent to demonstrated energy saving. The comparison should include actuator adjustment work and changes in positioning performance.

Robot-positioning studies and reviews of robot energy consumption address additional influences on measured energy [123,179]. They should not be cited as direct demonstrations of passive balancing when their actual intervention is trajectory or placement optimization.

The mechanism-balancing taxonomy separates static, force, moment, and inertia-related balancing objectives [180]. These objectives can overlap, but they are not identical. Reduced shaking forces or moments, improved balance, and lower electrical energy are distinct outcomes that need corresponding indicators.

For press design, a balancing choice should be linked to the targeted variable: gravity torque, shaking force, shaking moment, peak input torque, or motor losses. Added inertia may reduce one undesirable effect while increasing another. A taxonomy supports classification; it does not itself demonstrate an energy benefit.

Reviews of passive gravity compensation and dynamic balancing, together with robot-arm compensation implementations, provide supporting design context [173,181,182]. Their transfer should retain the relevant load assumptions and performance measures.

Four-bar spring compensators and variable-stiffness actuator designs illustrate complementary approaches [174,178]. A fixed compensator may suit a repeatable load, whereas adjustable mechanisms offer flexibility at the cost of additional hardware and possibly adjustment energy.

The effectiveness of a fixed passive compensator is generally specific to a payload, forming-force history, stroke, dwell, and acceleration profile. Changes in workpiece mass, material behavior, motion law, or cycle rate can shift the mechanism away from the bal-

anced condition and increase residual motor torque, shaking loads, or positioning error. Evaluation should therefore cover the representative production envelope. Adjustable compensation may widen that envelope, but its additional mass, adjustment time, control demand, and adjustment energy must also be included.

Passive mechanics should therefore be evaluated as one part of the complete drive. The useful question is whether a selected component improves the required motion, load transmission, or measured consumption over the intended operating envelope.

Hybrid storage reviews describe combinations of electrical, mechanical, and hydraulic media [183]. A similar integration principle may guide press design, but the choice of media should follow the measured cycle demand and recovery opportunities rather than a preference for the largest number of technologies.

The advent of composite actuators also introduces new paradigms for energy management in cyclic machinery. Unlike traditional multi-link passive compensators, which incur a severe penalty in added inertia, composite materials enable variable-stiffness control with a highly favorable force-to-weight ratio [34,35]. Moreover, these structures allow for structurally embedded energy harvesting. This capability directly complements the vibration harvesting strategies discussed in Section 5.5, enabling presses to recover energy and adjust mechanical compliance without the mass, complexity, and physical space requirements of external mechanical balancers.

5.7. Press-Specific Energy Studies

Press-specific studies provide the most relevant starting point for evaluating practical energy measures. Nevertheless, forming processes, machine sizes, and evaluation boundaries vary. Plant-level consumption, machine-cycle energy, and component efficiency should not be combined into a common improvement percentage.

Servo-press process optimization, quantitative stamping-energy evaluation, energy-based environmental assessment, and motor-consumption simulation address different questions [184–187]. To empirically substantiate the integrated design framework, it is crucial to examine specific, measurable performance metrics from existing experimental press studies. For example, Tso and Li [18] reported that, in a flywheel-assisted servo press, the servo drive contributed approximately 12% of the total stamping energy during a blanking operation, significantly reducing the peak load on the main motor. Similarly, Wen et al. [185] evaluated a 6300 kN multi-link servo press, recording an energy consumption of 0.0945 kWh per operation and a machine-input-to-slide energy-transfer efficiency of 39.5%. In their specific comparative setup, this represented an 86.4% reduction in energy consumption compared to a replaced 8000 kN hydraulic press. While these percentages (12% servo share, 86.4% energy savings) are specific to their respective reference boundaries and cannot be universally pooled as a generic standard, they empirically demonstrate that optimized hybrid architectures can fundamentally alter power distribution and yield measurable net cycle energy savings.

Hydraulic-press studies investigate energy-saving buffers and multi-stage pressure-source systems [153,154]. Their design principle is to better match the supply to phase-dependent demand. Reported gains remain specific to the studied circuit, reference case, forming load, and included losses.

Mechanical crank-press drive research provides an additional perspective on energy use [188]. A drive-level evaluation must be separated from facility-wide consumption that also includes heating, cutting, and other production operations. This distinction matters when estimating a press-drive intervention's contribution to total manufacturing demand.

Table 4 provides the quantitative press-specific evidence used to delimit the proposed framework. The values are retained as reported in the original studies and are not combined because they represent different quantities, reference machines, and accounting boundaries.

Table 4. Quantitative results reported in representative press-specific studies.

Study and Validation Context	Directly Reported Metric	Reference or System Boundary	Interpretation in This Review
[18]: flywheel-assisted hybrid servo press; blanking experiments	Servomotor torque approximately 15% of the flywheel torque; servomotor supplied 12% of total stamping energy.	Energy and torque distribution inside one prototype during the investigated blanking motion.	Direct evidence of actuator-power partition; not a net plant-energy saving or a universal cycle value.
[30]: manufactured Stephenson II press prototype; experimental verification	Maximum slide-guide reaction was 4.88% of the maximum slide force.	Comparison of theoretical and measured force distribution for the proposed mechanism.	Evidence of improved force transmission and guide loading; not an electrical-energy metric.
[185]: 6300 kN multi-link servo press; stamping-energy evaluation	0.0945 kWh per operation; 39.5% machine-input-to-slide energy-transfer efficiency; 86.4% lower energy consumption than the replaced 8000 kN hydraulic press.	Complete-machine comparison with a hydraulic press of different nominal capacity and architecture.	A process- and machine-specific comparison; it cannot be attributed solely to hybrid actuation.
[154]: hydraulic fine-blanking press with a multi-stage pressure-source system	76.87% reduction in flow-regulating-module energy loss and 13.53% reduction in overall energy dissipation.	Comparison with the conventional hydraulic system used as the study baseline.	The subsystem and whole-system percentages describe different boundaries and must not be conflated.

Recent press-specific and press-adjacent studies in the review corpus include pressure control of a pump-controlled hydraulic die cushion [69], hybrid coding control of an electrohydraulic pressure-servo system [104], and a multi-stage pressure-source system for a heavy-load hydraulic fine-blanking press [154].

5.8. Comparative Synthesis of Energy Measures

Table 5 separates demand shaping, hydraulic loss reduction, regeneration, buffering, and auxiliary harvesting. A storage device may accept energy, supply a peak, or do both; the actual circuit determines its function. Passive balancing may change actuator loading without reducing the material-deformation work.

Table 5. Functional comparison of energy-saving technologies for hybrid linkage and press systems.

Measure	Physical Role	Cycle Relevance and Limitations	Evidence
Electrical regeneration	Returns available negative power to a receiving load, store, or grid.	Useful during generating phases; limited by receiving capacity and drive losses.	Vehicle studies explain control principles [127,129,131]; press-specific energy accounting is still required.
Battery–supercapacitor storage	Buffers electrical power and energy demand.	Can support short peaks; adds conversion and standby losses.	Mostly vehicle and drive-system evidence [137,138,140,144].
Hydraulic accumulator	Stores pressure energy and buffers supply or recovery.	Charging, discharge, pressure limits, pre-charge, and thermal behavior determine benefit.	Hydraulic systems and presses [145,153,154,189].

Table 5. *Cont.*

Measure	Physical Role	Cycle Relevance and Limitations	Evidence
Efficient hydraulic architecture	Reduces unnecessary pressure or flow losses.	Relevant across hydraulic operating phases; depends on circuit and load matching.	Hydraulic reviews and servo-axis studies [146,150–152].
Flywheel	Stores kinetic energy and supports cyclic demand.	Peak buffering differs from net energy saving; standby and transmission losses remain.	Press blanking experiment [18]; storage-design reviews [155–157].
Passive mechanics	Shapes torque and redistributes reversible energy.	Load- and geometry-dependent; does not eliminate forming work.	Compensation and balancing studies [172–174,180].
Vibration harvesting	Converts oscillatory motion to auxiliary electrical supply.	Power budget, duty cycle, and mechanical loading must be measured.	Mostly suspension, bridge, and sensor-scale evidence [163–166,168].

A useful design sequence is to define the forming task and accounting boundary, remove avoidable losses, examine opportunities for negative-power recovery, and then size storage for the remaining demand. These decisions remain coupled and may require iteration. Storage should be justified by the resulting power-time profile.

Flywheels, accumulators, and capacitive stores can support short demand peaks when properly integrated. Regeneration is useful when a receiving path is available. Hydraulic supply control can reduce unnecessary pressure or flow losses. Vibration harvesting operates at a different scale and should be evaluated against auxiliary-load requirements.

Press and die-cushion studies provide relevant evidence for flywheel assistance, hydraulic buffering, pressure-source selection, and process control. Much of the battery–supercapacitor and vibration-harvesting literature concerns vehicles, renewable energy, or other structures. Those results identify possibilities for transfer; they do not establish press-scale savings.

Numerical comparisons must retain their original meaning. The 12% servo contribution in Tso and Li is a share of total stamping energy for their experiment [18]. It is not a universal saving or a complete electrical-cycle measurement. Similar care is needed for peak torque, installed power, recovered energy, and hydraulic-loss results.

The combined evidence supports evaluating mechanism, control, and energy decisions at the same system boundary. The following discussion develops an integrated framework and identifies the conditions needed to test it.

6. Discussion

Hybrid-actuated linkages should be evaluated as coupled mechanical, control, and energy systems. Topology and geometry determine feasible motion and transmission characteristics. Control realizes the selected trajectory under disturbances and constraints. The energy architecture supplies, stores, dissipates, and possibly recovers power. Improving one part can shift demand or losses elsewhere.

Figure 7 summarizes this integrated design view. Process requirements guide mechanism, controller, and energy-management choices; validation then checks the resulting motion, loading, and consumption. Application proximity and validation method are kept separate so that a related physical principle is not mistaken for full-scale press evidence.

The framework is a qualitative synthesis, not a validated universal design algorithm. Direct press studies, press-adjacent subsystem studies, and transferable evidence answer different questions. Within each group, analytical, numerical, and experimental findings should retain their own limitations.

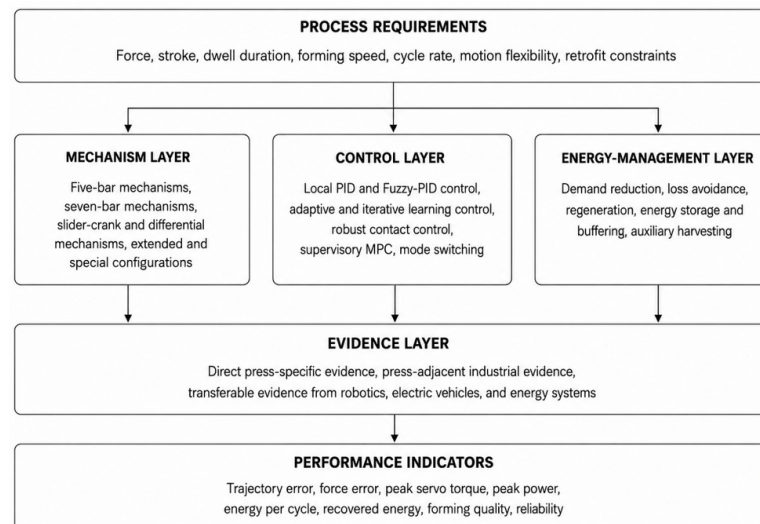


Figure 7. Integrated framework linking process requirements, mechanism selection, control, energy management, and validation. Authors' synthesis.

6.1. Coupling of Mechanism and Control

A programmable input does not make every output trajectory feasible. Geometry, assembly mode, transmission quality, and actuator limits determine the available motion. Five-bar mechanisms, seven-bar press linkages, and differential-based arrangements offer different compromises [15,16,21,25]. Their suitability depends on the task rather than on link count alone.

Control can compensate for some disturbances and model errors, but it cannot remove geometric or actuator constraints. Mechanism synthesis and trajectory design should therefore proceed together. Press-linkage experiments and motion-design studies provide complementary evidence [19,30]; neither independently establishes the performance of a complete integrated hybrid system.

Geometric changes can alter the required servo capacity and power distribution. These effects must be distinguished from changes in total electrical consumption. Stamping-energy partition in a flywheel-assisted press [18] and kinetostatic linkage analysis [25] show different indicators that should be evaluated together, not combined into a single percentage.

Control requirements change across approach, contact, forming, dwell, and return. A repeated task may benefit from learning compensation, while variable loads or constrained multi-axis operation may justify observer-based or predictive components. Press and die-cushion studies illustrate this coordination problem [14,68,69,97].

The reviewed studies do not establish a universal ranking of controllers. MPC can encode constraints and several objectives but depends on model adequacy and computation. PID or learning-based structures can be practical for repeatable operation. Robust and neural components address different uncertainty mechanisms. A fair comparison requires a common task, baseline, and implementation budget.

6.2. Energy Flow Through the Operating Cycle

A press cycle creates a time-varying power demand. Acceleration and forming can create peaks; deceleration or an overrunning load can provide negative mechanical power. Dwell may require sustained actuator effort even at zero ram speed. Idle periods may recharge storage while also consuming auxiliary or standby energy. Each phase belongs in the selected accounting boundary.

The design objective should distinguish required forming work, reversible mechanical energy, and avoidable losses. Linkage synthesis, motion planning, and balancing shape

demand; efficient drive and hydraulic architectures reduce losses; regenerative paths recover available power; storage buffers address supply–demand mismatch. None of these functions alone reduces total cycle consumption.

Flywheels and hydraulic accumulators are physically compatible with short cyclic demands, and relevant press or hydraulic-system studies support their evaluation [18,145,153,154,189]. Evidence on battery–supercapacitor and vibration-harvesting integration is mainly adjacent [140,164]. Integration should be justified based on the target machine’s measured power and auxiliary-load requirements.

At minimum, reports should identify energy per completed cycle, peak input power, peak actuator torque, cycle time, and forming quality. Storage-based comparisons should also report initial and final stored energy. Otherwise, apparent savings may reflect storage depletion rather than improved steady-cycle efficiency.

Net electrical energy savings should be evaluated as the difference in measured electrical input between technically comparable machines or operating strategies over a complete steady production cycle. The accounting boundary should include approach, forming, dwell or low-speed operation, return, idle or recharge, motors, converters, hydraulics, cooling, control hardware, and other relevant auxiliary equipment. Servo-energy share, peak torque reduction, recovered energy, installed power, and subsystem loss reduction should remain separate indicators and should not be reported as equivalent to net cycle-energy saving.

For a storage-assisted comparison, the initial and final energy states of the flywheel, capacitor, battery, or hydraulic accumulator should be equal, or their difference should be included explicitly in the reported balance. Otherwise, reduced grid input may simply represent depletion of a pre-charged store. Repeated steady-cycle measurements are therefore required to distinguish genuine loss reduction from temporary use of stored energy.

Figure 8 presents a qualitative phase-resolved representation of the power flow in a representative hybrid press cycle. During approach and forming, the main drive, flywheel, and servo input may supply positive mechanical power in proportions determined by the mechanism and prescribed motion. During dwell or low-speed forming, ram mechanical power may be small, although actuator torque, hydraulic pressure maintenance, and transmission losses can remain nonzero. During return and deceleration, the servo drive may transfer negative mechanical power to the DC bus, electrical storage, another axis, or the flywheel. The accounting boundary includes input energy, forming work, recovered energy, drive and hydraulic losses, auxiliary consumption, and changes in stored energy.

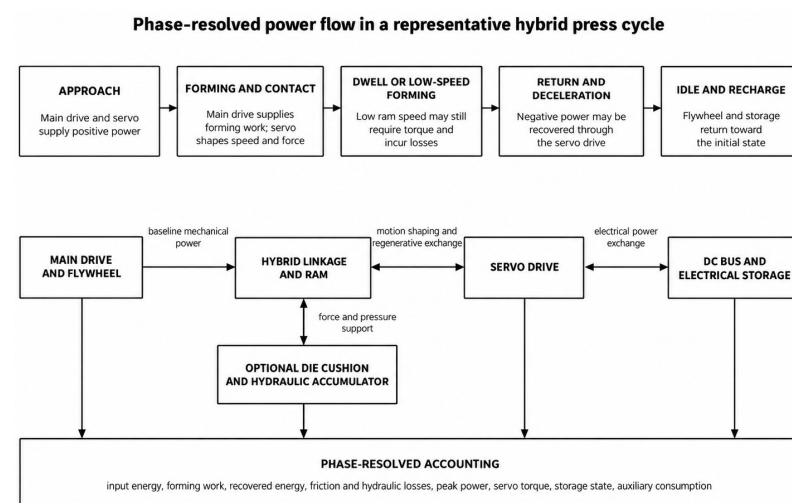


Figure 8. Qualitative phase-resolved power flow and accounting boundary for a representative hybrid press cycle. Authors’ synthesis.

6.3. Integrated Design and Evaluation

Table 6 maps representative requirements to candidate design features and evaluation priorities. It is a decision aid derived from the qualitative synthesis. The proposed combinations require task-specific validation and are not ranked as experimentally superior alternatives.

Table 6. Integrated selection matrix for hybrid-actuated press design, control, and energy management.

Requirement	Candidate Mechanical Features	Control and Energy Options	Validation Priorities
Controlled forming speed or dwell	Linkage and input trajectories synthesized for the required ram motion.	Coordinated motion/contact control; buffering where cycle demand justifies it.	Dwell error, input torque and speed, force accuracy, forming quality, net cycle energy.
Repetitive high-rate stamping	Geometry with feasible transmission and limited corrective drive demand.	Fast feedback, possible iterative learning; flywheel or electrical buffering.	Repeatability, cycle time, thermal duty, peak input power, steady-cycle energy.
Retrofit	Auxiliary-input or differential integration compatible with the existing drive.	Phase coordination and explicit torque/speed limits; evaluate existing storage and recovery paths.	Structural compatibility, required servo rating, power circulation, achievable stroke changes.
Hydraulic press or die cushion	Circuit matched to required force, pressure, and flow stages.	Mode switching, robust feedback or MPC; accumulator, pressure-source, or pump-control options.	Force/pressure tracking, transitions, hydraulic losses, storage state, cycle input energy.
Several production profiles	Sufficient geometric and actuator operating range.	Trajectory optimization and appropriate adaptation; storage sized from representative cycles.	Changeover, tracking across loads, constraint violations, storage and thermal limits.
Autonomous monitoring	Sensor locations with measured usable excitation.	Low-power sensing and local storage; harvesting only where the energy budget is adequate.	Harvested energy, sensor duty cycle, data continuity, durability, effect on the machine.

Design trade-offs are coupled. A longer dwell may alter servo effort; a faster return may increase peak power and braking demand; a larger store may reduce input peaks while adding standby losses. Passive compensation may suit one load but become less effective after a payload or trajectory change. Evaluating these interactions is more informative than comparing isolated components.

Optimization variables can include link dimensions, input trajectories, motor and converter ratings, storage capacity, accumulator pre-charge, controller parameters, and switching conditions. Objectives should distinguish productivity, forming quality, tracking, actuator stress, and net energy. Representative cycles and constraints should be defined before comparing candidate solutions.

To clarify the boundaries and practical application of the integrated framework shown in Figure 7, Table 7 applies it to an illustrative deep-drawing operation. The example assumes a prescribed ram stroke, a controlled low forming velocity, and, where the forming process requires it, a short dwell or low-speed interval near bottom dead center. At the mechanism layer, a hybrid seven-bar linkage is selected because its geometry and coordinated input trajectories can generate the required ram motion while the servomotor modulates the forming phase without stopping the constant-speed main drive. At the control layer, local PID feedback regulates the approach and return phases, while contact detection initiates a transition to robust force or pressure control during forming and

dwell. At the energy-management layer, the main-drive flywheel buffers forming-power demand and may be re-accelerated during lower-demand portions of the cycle, provided the measured power flow supports this operating mode. The framework does not predict a numerical performance improvement; instead, it identifies the coupled design choices and validation indicators needed to compare with a conventional press performing the same forming task.

Table 7. Illustrative application of the integrated framework to a hybrid deep-drawing press.

Framework Layer	Illustrative Application to the Deep-Drawing Operation	Required Validation
Process requirements	Prescribed ram stroke, controlled low forming velocity, short dwell or low-speed interval near bottom dead center, specified cycle time, and required part quality.	Ram displacement and velocity profiles, dwell duration and error, forming force, cycle time, dimensional accuracy, and springback or surface-quality indicators where applicable.
Mechanism layer	Hybrid seven-bar linkage with the geometry and the two input trajectories synthesized together to generate the required approach, forming, dwell, and return motion.	Feasible workspace, transmission quality, input-speed limits, peak and root-mean-square servo torque, sensitivity to joint clearance, and load transmission near the forming region.
Control layer	Local PID position control during approach and return; contact detection followed by position–force or position–pressure switching; robust force regulation during forming and dwell.	Trajectory error, force or pressure error, switching transient, contact-detection accuracy, closed-loop stability, actuator saturation, and computational requirements.
Energy-management layer	Flywheel-supported constant-speed main drive; the flywheel supplies part of the forming-power peak and is re-accelerated during lower-demand phases when permitted by the cycle power balance.	Flywheel-speed variation, peak input power, peak servo power and torque, servomotor energy share, losses in the drive path, and net electrical energy per completed steady cycle.
Evidence and comparison boundary	The case is a theoretical use of the framework and not a validated press design or a prediction of a specific energy-saving percentage.	Comparison with a conventional or alternative press using the same workpiece, forming load, motion profile, cycle rate, production boundary, and initial and final stored-energy states.

This illustrative case shows that the proposed framework serves as a structured design and measurement guide rather than a universal performance predictor; task-specific modeling and experimental validation remain necessary to quantify any improvement.

6.4. Main Implications and Research Priorities

The first implication is that actuator work must be designed. Motion programmability is useful only within feasible torque, speed, and thermal limits. Low-speed or dwell capability should be evaluated with the associated input motion and energy flow, rather than attributed to topology alone.

The second implication is that control methods complement one another. Local regulation, adaptation, learning, disturbance rejection, predictive coordination, and mode switching address different functions. An integrated architecture should include only the functions justified by its task and validation results.

The third implication is that application relevance and validation strength must remain explicit. A mechanism simulation for a press, an experiment on a hydraulic axis, and a vehicle energy-management study offer different kinds of support. They should not be counted as equivalent demonstrations of full-machine press performance.

Cross-study comparisons remain limited by inconsistent metrics and boundaries. Future studies should report the reference machine, forming work, load and motion profiles, cycle time, included auxiliaries, storage state, and measured electrical input. Percentage improvements are meaningful only with these conditions identified.

A deeper analysis of the reviewed literature reveals significant practical bottlenecks in transferring advanced theoretical methods to industry. For instance, while Model Predictive Control (MPC) offers excellent constraint management, its computational latency can be prohibitive for high-rate stamping operations that require millisecond-level reaction. Similarly, complex multi-link balancing mechanisms or continuous position-force mode switching can introduce wear, friction, and reliability issues under heavy forming loads. Therefore, the theoretical benefits of kinematic flexibility and advanced energy optimization must always be critically weighed against the dynamic complexity and maintenance penalties they incur in a real-world manufacturing environment.

A useful next step is a common experimental comparison in which geometry, controller, and energy measures are evaluated on the same forming task. Ablation or controlled component comparisons could distinguish the contribution of each intervention from their combined effect. The present synthesis does not establish that such an integrated configuration is already optimal.

A minimum benchmark should use the same workpiece material and geometry, forming-force history, ram stroke and motion law, production rate, part-quality requirement, ambient and thermal conditions, and actuator constraints. All candidate mechanisms, controllers, and storage options should be evaluated over repeated steady cycles using the same electrical and mechanical accounting boundary. Reported quantities should include forming work, peak and root-mean-square actuator torque, peak grid power, net electrical energy per cycle, drive and hydraulic losses, storage-state change, auxiliary consumption, cycle time, tracking and force errors, thermal duty, and measurement uncertainty. Percentage improvements should be stated only relative to a clearly defined and technically comparable baseline.

The isolated contribution of hybrid actuation should be determined through a staged comparison: first, the reference single-input press; second, the same or an equivalent platform after general modernization of motors, converters, sensing, and low-level control; third, the modernized single-input system with trajectory optimization; fourth, the same task with the auxiliary hybrid input enabled but without additional storage or passive balancing; and finally, the complete system with regeneration, storage, or balancing. The difference between the third and fourth stages provides the closest estimate of the auxiliary hybrid-actuation contribution, while the subsequent stages identify the additional effects of energy-management measures. Exact attribution requires the task, baseline, hardware, and accounting boundary to remain otherwise unchanged.

Further validation should address clearance, friction, compliance, wear, thermal behavior, storage degradation, and sensing or computation delays. These factors can alter both tracking and energy flow over time. Reporting their influence would improve the transfer of laboratory results to production machinery.

7. Conclusions

This review's main contribution is an integrated, evidence-graded framework that connects hybrid-linkage topology, control function, energy-management architecture, and measurable press-performance indicators. Its novelty lies in treating these elements as coupled design variables, separating direct press evidence from press-adjacent and transferable evidence, and comparing quantitative results without pooling incompatible metrics.

The review shows that no mechanism topology or controller is universally superior. Five-bar systems offer a compact basis for programmable motion, seven-bar press

linkages provide additional freedom for shaping the ram trajectory, and differential or auxiliary-input arrangements support retrofit concepts. Local feedback, adaptation or iterative learning, robust compensation, predictive coordination, and mode switching address different control functions. Representative press studies report study-specific outcomes: a 12% servomotor share of stamping energy in one flywheel-assisted blanking prototype; 0.0945 kWh per operation and 86.4% lower consumption than a replaced hydraulic press in one complete-machine comparison; and a 13.53% reduction in overall hydraulic-system energy dissipation for one multi-stage pressure-source design. These values are not interchangeable and do not establish a universal saving.

Practically, the framework can guide the design and evaluation of blanking, deep-drawing, hydraulic-press, die-cushion, and retrofit systems by linking process requirements to mechanism selection, controller organization, storage or regeneration options, and validation metrics. The theoretical deep-drawing case demonstrates how the framework defines a testable design path rather than predicting performance in advance.

Future work should evaluate integrated designs on common press tasks with explicit energy-accounting boundaries, equal initial and final storage states, repeated-cycle thermal conditions, and measured part quality. Composite hydraulic actuators and multifunctional compliant structures are promising because of their reduced mass and tailorable stiffness or damping, but their fatigue, sealing, force accuracy, embedded sensing or harvesting, and net cycle-energy effects require complete-actuator and press-scale experiments.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Meaning
ANFIS	Adaptive neuro-fuzzy inference system
CPG	Central pattern generator
DC	Direct current
DOF	Degree of freedom
FOPID	Fractional-order proportional–integral–derivative
MPC	Model predictive control
NN	Neural network
PID	Proportional–integral–derivative
SCARA	Selective compliance assembly robot arm

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