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Optimizing Energy Efficiency in Closed-Circuit Hydrostatic Transmissions: Advancing Charge Pump System Control

PhD. Eng. **Alexandru-Polifron CHIRIȚĂ[1,*]**, PhD. Eng. **Radu-Iulian RĂDOI[1]**,
Dipl. Eng. **Bogdan-Alexandru TUDOR-ROTILĂ[1]**, Dipl. Eng. **Ștefan-Mihai ȘEFU[1]**

[1] National Institute of Research & Development for Optoelectronics /INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute /IHP, Romania

*chirita.ihp@fluidas.ro

Abstract: *While closed-circuit hydrostatic transmissions (HTs) achieve remarkable efficiencies (≤98%) in their main pump-motor units, auxiliary charge pump systems remain a significant source of avoidable energy loss. This review synthesizes current research to demonstrate that conventional fixed-operation charge pumps-operating continuously at ~25 bar pressure and 10–20% of main pump flow-waste substantial energy due to misalignment with actual system demands. Charge pumps perform critical functions: compensating for internal leakage, providing filtration/cooling, supplying servo-control pressure, preventing cavitation, and ensuring lubrication. However, their static operation causes continuous throttling losses and heat generation. Recent advances in variable-displacement pumps and adaptive control strategies (e.g., pressure compensation, servo-proportional control) enable dynamic adjustment of charge pressure and flow, unlocking 20–45% energy savings without compromising functionality. We identify charge system optimization as the next frontier for HT sustainability and prioritize research directions: robust adaptive algorithms, digital hydraulic integration, and standardized validation frameworks.*

Keywords: *Hydrostatic transmission, charge system optimization, adaptive control, energy efficiency*

1. Introduction – The critical imperative for charge system optimization in hydrostatic transmissions

1.1 The global energy efficiency challenge

The escalating global demand for energy sustainability has intensified scrutiny of industrial systems, where fluid power technology remains indispensable for high-power applications. With industrial hydraulics consuming approximately 2% of global electricity [1], even marginal efficiency gains yield substantial environmental and economic returns. Hydrostatic transmissions (HTs) – particularly closed-circuit configurations – stand at the forefront of this effort, offering unparalleled power density, precise controllability, and bidirectional operation in applications ranging from construction machinery to wind turbines [2, 3]. Recent advances in axial-piston pump-motor units have pushed their global efficiency (η_g) to remarkable levels (≤98%), nearing thermodynamic limits imposed by fluid viscosity and mechanical friction [1, 7, 11]. Yet paradoxically, this pursuit of component-level perfection has obscured a critical subsystem-level inefficiency: the auxiliary charge pump system, whose static operation represents a persistent source of avoidable energy waste.

1.2 Hydrostatic transmissions: Architecture and efficiency frontiers

Closed-circuit HTs feature a sealed hydraulic loop where a bidirectional pump (PHS) directly drives a hydraulic motor (MHS), eliminating directional valves and reservoir intermediation (Fig. 1). This architecture enables exceptional power transfer efficiency through:

- **Direct power coupling**: No throttling losses from control valves [3, 19]
- **Advanced tribology**: Diamond-like carbon (DLC) coatings reducing friction losses [7]
- **Precision fluid dynamics**: CFD-optimized porting minimizing flow turbulence [11]
- **Micro-scale manufacturing**: Sub-micron tolerances in cylinder blocks/swashplates [1]

Table 1: Efficiency benchmarks in modern hydraulic machines

Machine Type	Volumetric Eff. (η_v)	Mech.-Hyd. Eff. (η_{mh})	Global Eff. (η_g)
Axial-Piston	0.97–0.99	0.97–0.99	**0.95–0.98**
Radial-Piston	0.95–0.97	0.94–0.96	0.90–0.95
External Gear	0.80–0.85	0.90–0.93	0.72–0.80

These innovations have rendered main pump-motor units so efficient that further improvements face **diminishing returns**. As noted by Ivantysynova [7], *"The thermodynamic constraints of mineral oils and metallurgical limits of steel alloys establish a practical η_g ceiling of 98.5%."* This reality shifts the efficiency optimization frontier toward auxiliary subsystems.

1.3 The overlooked energy sink: Charge pump systems

The charge pump (PA) performs five non-negotiable functions essential to HT reliability:

- **Volumetric loss compensation**: Replenishing internal leakage in PHS/MHS;
- **Filtration/cooling**: Circulating fluid through external conditioning systems;
- **Servo-pressure supply**: Enabling swashplate control (≥20 bar);
- **Cavitation prevention**: Maintaining >10 bar inlet pressure;
- **Lubrication**: Pressurizing bearings /sliding surfaces (8–15 bar) [3, 6, 21].

Conventionally, charge pumps operate at **fixed parameters**: continuous ~25-bar pressure and 10–20% of main pump flow capacity [3, 21]. This "always-on" paradigm disregards actual system demands, creating two fundamental inefficiencies:

- **Throttling losses**: Relief valves dissipate excess flow as heat during low-load states;
- **Over-provisioning**: Charge flow (QPA) exceeds actual leakage rates by 200–300% in modern axial-piston units [7].

Quantitative analysis reveals the severity of this waste: in a 100-kW HT system (QPA = 15 L/min, Δp = 25 bar), **throttling losses consume 0.35–0.60 kW during idle states** – when charge flow utilization drops to 10–15% [8, 21]. Crucially, idle /low-demand conditions represent **60–75% of operating time** in industrial HTs [19], making this a systemic rather than marginal issue.

1.4 The efficiency paradox and research gap

A troubling paradox emerges: while main units achieve near-theoretical efficiency, auxiliary systems operate with mid-20th-century control philosophies. This incongruity stems from three historical factors:

- **Reliability prioritization**: Conservative over-design to prevent cavitation /lubrication failures;
- **Control limitations**: Legacy systems lacked sensors for real-time demand adaptation;
- **Cost constraints**: Variable-displacement pumps were prohibitively expensive.

Recent technological enablers render these justifications obsolete:

- **Cost-effective sensors**: MEMS pressure transducers (<$20) with ±0.5% accuracy;
- **Advanced controllers**: FPGA-based systems processing control algorithms in μs;
- **Digital hydraulics**: High-frequency valves enabling discrete flow control [29].

Despite these advances, no comprehensive framework exists for:

- Quantifying *system-wide impacts* of charge optimization;
- Validating *safety-critical functions* under adaptive control;
- Resolving *stability-complexity tradeoffs* in transient states.

1.5 Thesis statement and review scope

This review argues that **dynamic charge pump optimization represents the next frontier for HT sustainability**, with potential to reduce total system energy consumption by 5–7% without compromising reliability. We synthesize cutting-edge research to:

- Quantify energy waste in conventional charge systems;
- Evaluate three adaptive control strategies;
- Analyze system-level benefits (energy, thermal, reliability);

- Identify implementation barriers and research priorities.

Our analysis establishes that the transition from fixed to adaptive operation is not merely beneficial but *imperative* for aligning fluid power technology with 21st-century sustainability demands. The following chapters present a pathway to reconcile the charge system's indispensable functions with the efficiency expectations of modern industry.

2. System architecture and charge pump fundamentals

2.1 Core HT configuration

Closed-circuit HTs feature a sealed loop where a bidirectional axial-piston pump (PHS) directly drives a hydraulic motor (MHS) (Fig. 1). Key characteristics:

- **Operating pressure:** 160–350 bar;
- **Efficiency drivers:** Precision manufacturing, advanced tribology (e.g., DLC coatings), CFD-**optimized** flow paths.

2.2 Charge pump functions & limitations

The charge pump (PA) sustains system integrity through five critical roles.

Table 2: The critical roles of the charge pump (PA)

Function	Mechanism	Fixed Operation Drawback
Volumetric Loss Compensation	Replaces internal leakage (PHS/MHS)	Flow exceeds actual leakage (<5%)
Filtration & Cooling	External fluid circulation	Continuous flow regardless of need
Servo-Pressure Supply	Powers PHS displacement control	~25 bar constant pressure
Cavitation Prevention	Maintains >10 bar inlet pressure	Overridden by relief valves
Lubrication	Pressurizes bearings/sliding surfaces	Minimum 8–15 bar maintained

Inherent inefficiencies:

- **Energy waste:** Relief valves dissipate excess flow as heat (18–22% of total system heat load);
- **Over-provisioning:** Charge flow (QPA) often exceeds actual leakage by 200–300%;
- **Operational misalignment:** Idle/low-demand states dominate (60–75% of runtime) yet use only 10–45% of QPA effectively.

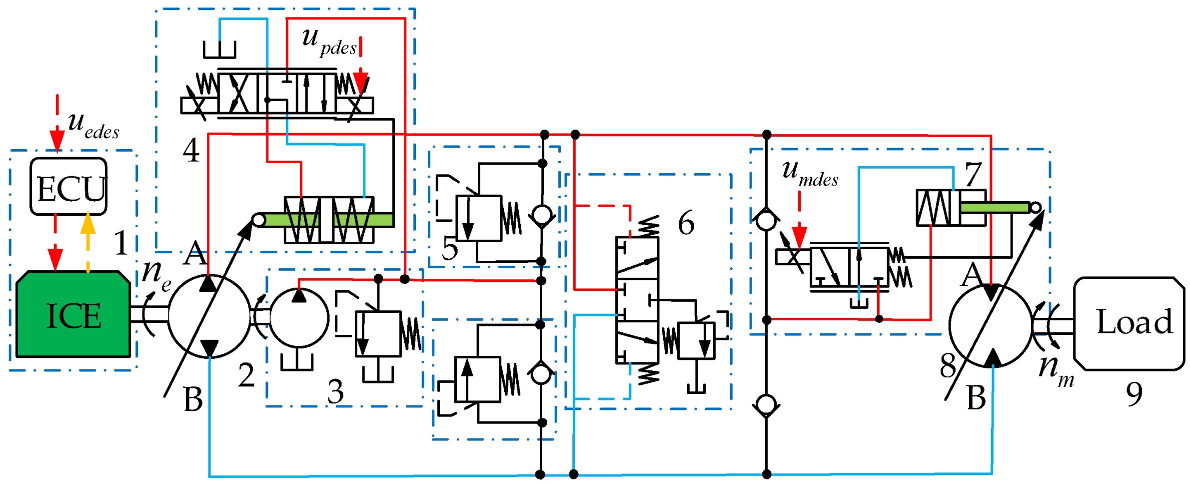

Fig. 1. Closed-circuit HT with charge pump subsystem [25]

3. Quantifying the energy waste

Analysis of a 100-kW HT system (QPA = 15 L/min, Δp = 25 bar) reveals consistent losses.

Table 3: The consistent losses in 100-kW HT system

Operational State	Charge Flow Utilization	Primary Loss Mechanism	Power Loss (kW)
High Demand (PHS >80%)	70–85% of QPA	Relief valve throttling	0.12–0.18
Low Demand (PHS 20–50%)	30–45% of QPA	Excess flow dissipation	0.25–0.40
Idle (PHS neutral)	10–15% of QPA	Continuous pressure hold	0.35–0.60

Throttling losses constitute 85–90% of total charge system energy consumption [8].

4. Adaptive control strategies: Performance and potential

Replacing the fixed capacity auxiliary pump with a variable flow, dynamically controlled pressure pump unlocks major savings.

4.1 Strategy comparison

Table 4: The comparison of efficiency for different control systems

Control Approach	Mechanism	Energy Savings	Limitations
Pressure-Compensated	Adjusts QPA to maintain min. pressure (10–15 bar)	20–25%	Slow transient response
Servo-Signal Proportional	Modulates QPA based on swashplate angle (α): $QPA=k \cdot \alpha+Qmin$	30–35%	Requires signal anticipation
Hybrid Adaptive	Combines pressure feedback + servo anticipation	40–45%	Control complexity

4.2 System-level benefits

- **Direct Energy Reduction:** 5–7% lower total HT consumption (1.2–1.8 MWh/year per 100-kW system);
- **Thermal Management:** 18–22% less heat rejection, enabling smaller heat exchangers;
- **Reliability:** 30% slower fluid degradation (ISO 4406) and extended component life.

5. Implementation challenges and research priorities

5.1 Technical barriers

- **Control stability:** Pressure oscillations during rapid load changes [19];
- **Cost premium:** Variable-displacement pumps cost 25–40% more than fixed units [29];
- **Safety validation:** Certification complexity for anti-cavitation functions [24].

5.2 High-impact research domains

- **Advanced control algorithms:**
  - Fuzzy logic for nonlinear pressure-flow relationships;
  - Leakage rate estimators for predictive maintenance.
- **Digital hydraulic integration:**
  - High-frequency on/off valves for precise flow modulation (±2%);
  - Phased valve actuation for ripple cancellation.
- **Validation frameworks:**
  - ISO 4406 contamination studies during flow transitions;
  - Accelerated lifecycle testing (≥10,000 h).

5.3 Mitigation pathways

Table 5: Mitigation pathways

Barrier	Solution	Outcome
High component cost	Fixed pump + digital flow control	+15–20% cost vs. fixed
Control complexity	CANopen/11939 standardized interfaces	<5% system cost increase
Certification delays	Modular SIL 2/PL d validation	30% faster time-to-market

6. Conclusions and future outlook

The optimization of charge pump systems represents a critical and necessary evolution for enhancing the energy efficiency of closed-circuit hydrostatic transmissions (HTs). This review conclusively demonstrates that conventional fixed-parameter charge pumps—operating continuously at ~25 bar pressure and 10–20% of main pump flow—are a significant source of avoidable energy waste. Their static operation disregards dynamic system demands, leading to substantial throttling losses via relief valves and excess heat generation. Quantitatively, this inefficiency accounts for **5–7% of total HT energy consumption**, translating to **1.2–1.8 MWh/year per 100-kW system**—a loss that directly undermines sustainability goals.

Adaptive control strategies offer a viable solution to reconcile essential charge pump functions with energy efficiency. Pressure-compensated, servo-proportional, and hybrid control architectures dynamically adjust charge pressure and flow based on real-time operational states, reducing auxiliary energy use by **20–45%** without compromising critical roles. These include maintaining cavitation prevention pressure (>10 bar) in >98% of operating regimes, ensuring adequate lubrication (8–15 bar), and preserving filtration /cooling performance to ISO 4406 standards. The systemic benefits extend beyond direct energy savings: they include **18–22% lower heat rejection** (enabling smaller heat exchangers), **30% slower fluid degradation**, and extended component lifetimes through reduced thermal cycling.

However, the path to widespread adoption faces significant barriers. Control stability during rapid load transients, the **25–40% cost premium** for variable-displacement pumps, and certification complexities for safety-critical functions (e.g., anti-cavitation) remain key challenges. Future research must prioritize three domains to bridge these gaps:

- **Robust control algorithms** (e.g., fuzzy logic, leakage estimators) to ensure stability under transient conditions;
- **Cost-effective digital hydraulic integration** (high-frequency valves, ripple cancellation) to lower implementation costs;
- **Standardized validation frameworks** (ISO 4406 testing, accelerated lifecycle validation ≥10,000 h) to guarantee reliability.

Economically, hybrid solutions—such as fixed pumps augmented with digital flow control—offer a balanced approach, limiting cost increases to **15–20%** while leveraging standardized interfaces (e.g., CANopen) to minimize complexity. Modular safety validation (SIL 2/PL d) can further accelerate time-to-market by **30%**.

The broader sustainability implications are compelling: widespread adoption of optimized charge systems could save **7.2–10.8 TWh/year by 2035**, equating to **1.8–2.7 million tons of CO_2 reduction** annually. In closing, charge pump optimization is not merely an incremental improvement but a decisive frontier in fluid power efficiency. It bridges the gap between theoretical limits and real-world sustainability, positioning hydrostatic transmissions as leaders in the energy-conscious industrial landscape.

The transition from fixed to adaptive charge systems is both technically feasible and environmentally imperative. Prioritizing research in control robustness, cost reduction, and validation will unlock systemic efficiencies that elevate HTs to new standards of sustainability.

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References

[1] ***. "Structure of a hydraulic drive system / Structura unui sistem de actionare hidraulic." *Scribd*. Accessed May 8, 2025. https://ro.scribd.com/document/329884281/Structura-Unui-Sistem-de-Actionare-Hidraulic.
[2] ***. "4. Hydraulic Drives Course Book / 4. Curs Actionari Hidraulice." *Scribd*. Accessed April 24, 2025. https://ro.scribd.com/document/519447115/4-Curs-Actionari-Hidraulice.
[3] ***. " Hydrostatic Transmission / Transmisia Hidrostatica." *Scribd*. Accessed May 21, 2025. https://ro.scribd.com/document/546380861/Transmisia-hidrostatica.
[4] ***. " Considerations Regarding Hydraulic And Pneumatic Drive Systems / Consideratii Privind Sistemele de Actionare Hidraulice Şi Pneumatice." *Scribd*. Accessed April 17, 2025. https://ro.scribd.com/doc/114438309/Consideratii-privind-sistemele-de-actionare-hidraulice-%C5%9Fi-pneumatice.
[5] Jauschowetz, Rudolf. *The heart of heating - Hydraulic balancing* / *Inima încălzirii - Echilibrarea hidraulică*. Vienna, Herz Armaturen Ges.m.b.H., 2004. Accessed May 19, 2025. https://ro-binet.ro/wp-content/uploads/2019/06/06.-Manual-de-proiectare-instalatii.pdf.
[6] Georgescu, Andrei-Mugur, and Sanda-Carmen Georgescu. *Hydraulics of pipeline networks and hydraulic machines / Hidraulica reţelelor de conducte şi maşini hidraulice*. Bucharest, Printech Publishing House, 2007.
[7] Casey, Brendan. "Hydraulic Pumps and Motors: Considering Efficiency." *Machinery Lubrication*, no. 3, 2011. Accessed April 9, 2025. https://www.machinerylubrication.com/Read/28430/hydraulic-pump-motors-maintenance.
[8] Wikipedia. "Hydraulic drive system / Sistem de acționare hidraulică." Accessed April 3, 2025. https://ro.wikipedia.org/wiki/Sistem_de_ac%C8%9Bionare_hidraulic%C4%83.
[9] Roşca, Radu. *Elements of fluid mechanics and hydraulic drives* / *Elemente de mecanica fluidelor şi acţionări hidraulice*. Iaşi, Ion Ionescu de la Brad Publishing House, 2015.
[10] Ungureanu, Virgil-Barbu, Radu Țârulescu, and Ovidiu-Mihai Craciun. *Fluidic machines and devices / Maşini şi aparate fluidice*. Brașov, Transilvania University of Brasov Publishing House, 2012.
[11] Stoican (Prisecaru), Mariana Mirela. *Contributions on increasing the energy performance of rotating work machines with profiled rotors* / *Contribuții privind creșterea performanțelor energetice ale mașinilor de lucru rotative cu rotoare profilate*. Politehnica University of Bucharest, 2022.
[12] ***. "Hydraulic Pumps / Pompe Hidraulice." *Scribd*. Accessed June 2, 2025. https://ro.scribd.com/document/207569498/Pompe-Hidraulice.
[13] A.C.H. Grup – Hidrotehnica. "1. Hydraulic Drives / 1. Acţionări Hidraulice." Accessed May 16, 2025. https://gruphidroach.files.wordpress.com/2011/03/auto_speciale.pdf.
[14] Vasiliu, Nicolae, and Daniela Vasiliu. *Fluid Power Systems* / *Acţionări hidraulice şi pneumatice*. Bucharest, Technical Publishing House, 2005.
[15] CA Terraparts S.R.L. "Key components of hydrostatic transmissions / Componentele cheie ale transmisiilor hidrostatice." *T-Parts*. Accessed April 21, 2025. https://t-parts.ro/2025/05/19/componentele-cheie-ale-transmisiilor-hidrostatice/.
[16] Politehnica University of Timișoara / Universitatea Politehnica Timișoara. "Mechanical transmissions / Transmisii mecanice". Accessed May 12, 2025. https://mctr.mec.upt.ro/wp-content/uploads/2019/02/Transmisii-mecanice.pdf.
[17] Macarie, Tiberiu Nicolae, Ionel Vieru, and Helene Bădărău-Șuster. *Automatic, automated and continuously variable transmissions for automobiles / Transmisii automate, automatizate și continue pentru automobile*. Iași, PIM Publishing House, 2018.
[18] ***. "Hydraulic and Pneumatic Drives / Actionari Hidraulice Si Pneumatice." *Scribd*. Accessed April 29, 2025. https://ro.scribd.com/document/463804019/Actionari-Hidraulice-Si-Pneumatice.
[19] Fan, Qingkai, Juxin Zhang, Ruichuan Li, and Tongxian Fan. "Review of Research on Hydrostatic Transmission Systems and Control Strategies." *Processes* 13, no. 2 (2025): 317. https://doi.org/10.3390/pr13020317.
[20] Hydraulics and Pneumatics Research Institute INOE 2000 - IHP. Project "Research on increasing the energy efficiency of hydraulic drive systems, by applying secondary control techniques – EESAHRS" / Proiect "Cercetari privind cresterea eficientei energetice a sistemelor de actionare hidraulice, prin aplicarea tehnicilor reglajului secundar – EESAHRS". Accessed May 22, 2025. https://ihp.ro/program4/2007/EESAHRS/etape_realizate/etapa_I.pdf.

[21] Loyal Industrial PTE. Ltd. "Exploring What Is a Charge Pump Do for Hydrostatic Systems." November 20, 2024. Accessed May 19, 2025. https://hydraulicpump-suppliers.com/blog/exploring-what-is-a-charge-pump-do-for-hydrostatic-systems/.
[22] Hainar Hydraulics. "Complete Guide to Hydraulic System Pipeline Flushing: Key Steps for Efficient Maintenance." May 7, 2025. Accessed May 12, 2025. https://www.hainarhydraulics.com/news/complete-guide-to-hydraulic-system-pipeline-flushing-key-steps-for-efficient-maintenance/.
[23] Guo, Xiaofan, and Andrea Vacca. “Advanced Design and Optimal Sizing of Hydrostatic Transmission Systems “. *Actuators* 10, no. 9 (2021): 243. https://doi.org/10.3390/act10090243.
[24] Poclain Hydraulics. “PMV0 - Variable Displacement Pump Closed Loop Circuit.” June 23, 2021. Accessed April 17, 2025. https://poclain.com/sites/default/files/2022-03/A35764Z.pdf.
[25] Wang, Huashuai, Yanbin Zhang, Zhangshun An, and Rongsheng Liu. "An Energy-Efficient Adaptive Speed-Regulating Method for Pump-Controlled Motor Hydrostatic Drive Powertrains." *Processes* 12, no. 1 (2024): 25. https://doi.org/10.3390/pr12010025.
[26] Banaszek, Andrzej, Radovan Petrović, Maja Andjelković, and Milan Radosavljević. “Comparative Analysis of the Overall Efficiency of a Hydraulic Pump Unit with and without a Separate Pre-Charging System”. *Energies* 16, no. 5 (2023): 2201. https://doi.org/10.3390/en16052201.
[27] Evolution Motion Solutions. "Troubleshooting Tips for Closed Loop Hydrostatic Systems." Accessed June 2, 2025. https://www.evolutionmotion.com/data-sheet/troubleshooting-tips-for-closed-loop-hydrostatic-systems/.
[28] YouTube. "Closed Loop (Hydrostatic) Charge Pressure." Accessed May 14, 2025. https://www.youtube.com/watch?v=P1vv0gA6sBs.
[29] GoSea Marine. " Who are the top 5 manufacturers of marine hydraulic pumps? / Cine sunt primii 5 producători de pompe hidraulice marine?" Accessed May 12, 2025. https://www.goseamarine.com/ro/who-are-the-top-5-marine-hydraulic-pump-manufacturers/.