



UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Tesis de Magister

Design and Sizing of an Energy Storage System for a Hybrid Tugboat

Tesis para optar al título de
Magister en Ciencias de la Ingeniería Electrónico

Alumno
Leonardo Solis Zamora

Profesor Guía
Dr. Marcelo Pérez Leiva

Comisión evaluadora
Nombre del primer correferente, Correferente, UTFSM
Nombre del segundo correferente, Correferente, CODELCO

Enero 2025 , Valparaíso, Chile

This is the dedicatory page.

Agradecimientos

This is the abstract

Resumen

This is the abstract

Abstract

This is the abstract

Índice general

Agradecimientos	ii
Resumen	iii
Abstract	iv
1. Simulation results	1
1.1. Battery Cell	1
1.2. Battery Bank	3
1.3. Power Converter Battery	4
1.4. Electric Motor	5
1.5. Diesel Propulsion Engine	6
1.6. Propeller	6
Bibliografía	7

Índice de figuras

1.1. PowerTrain	1
1.2. BattCell in power train.	1
1.3. Cell model zero order Shepherd.	2
1.4. Implementation Model of zero order Shepherd.	3
1.5. BattBank in power train.	3
1.6. BattBank voltage profile.	4
1.7. BattBank Electrical behavior.	4
1.8. Power Converter Bank.	5
1.9. ElectricMotor in power train.	5
1.10. Diesel Propulsion Engine in power train.	6
1.11. Propeller in power train.	6

Índice de tablas

1.1. Valores de los parámetros del modelo Sheperd clásico y ajustado para una celda de batería.	2
1.2. Valores de los parámetros del modelo Batt Bank	3

Capítulo 1

Simulation results

The last step here, is to simulate the power train, related with all the elements inside, as battery bank, power converters, electric motor, etc.

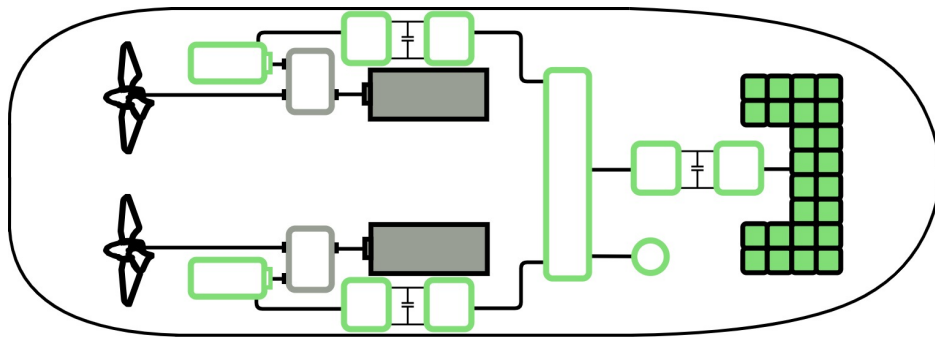


Figura 1.1: PowerTrain

1.1. Battery Cell

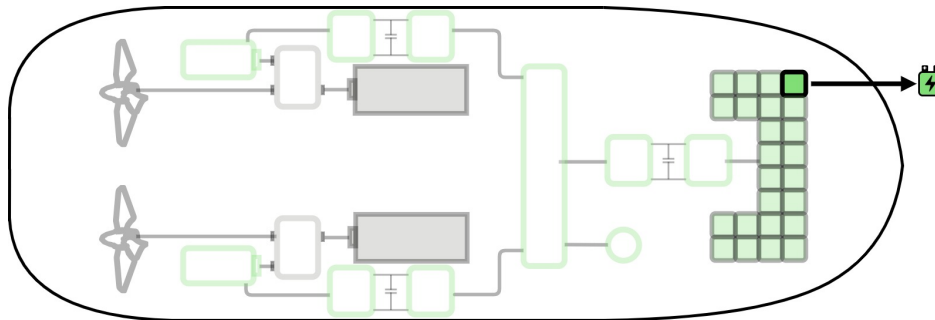


Figura 1.2: BattCell in power train.

The battery bank's design parameters are used to select a cell for electrical modeling with a Shepherd model of order 0. Technical details of the chosen cell, U27-36XP from Valence, are used to find model parameters that closely match its real discharge curve. The model shows good similarity to the actual performance, as illustrated in Fig. 12. This enables the extrapolation of results to model a battery bank and predict its behavior across various operating profiles.

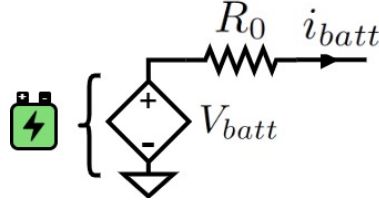


Figura 1.3: Cell model zero order Shepherd.

$$V_{batt} = V_0 - K \frac{Q_0}{Q_0 - Q} Q + A \cdot e^{-BQ} \quad (1.1)$$

$$Q = \int_0^t i_{batt}(t) dt \quad (1.2)$$

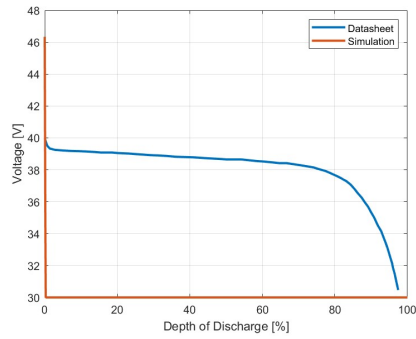
- V_{batt} : no load voltage [V].
- V_0 : Battery constant voltage [V].
- K : Polarizing voltage/resistance factor [V].
- Q : Actual battery capacity [Ah].
- Q_0 : Battery capacity [Ah].
- A : Exponential zone voltage amplitude [V].
- B : Exponential zone time constant inverse [Ah]⁻¹

[Agregar imagen de ajuste de curva](#)

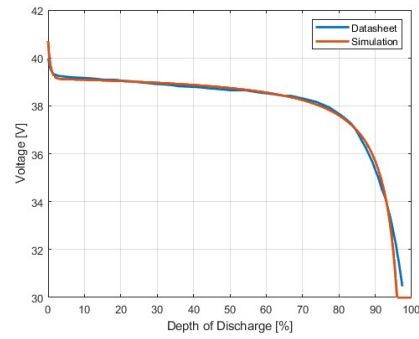
$$\begin{aligned}
 A &= V_{full} - V_{exp} \\
 B &= \frac{3}{Q_{exp}} \\
 K &= \frac{(V_{full} - V_{nom} + A(e^{-B \cdot Q_{nom}} - 1))\Delta Q}{Q_{full}} \\
 V_0 &= V_{full} + K + R \cdot I_{nom} - A \\
 \Delta Q &= Q_{full} - Q_{nom}
 \end{aligned} \quad (1.3)$$

Tabla 1.1: Valores de los parámetros del modelo Sheperd clásico y ajustado para una celda de batería.

Parámetro	Shepherd clásico	Sheperd ajustado
A	2.4 [V]	1.44 [V]
B	3 [Ah ⁻¹]	3 [Ah ⁻¹]
K	1.2857 [V]	0.0051 [V]
V ₀	43.9357 [V]	39.2536 [V]



(a) Classic Shepherd



(b) Adjusted Shepherd

Figura 1.4: Implementation Model of zero order Shepherd.

1.2. Battery Bank

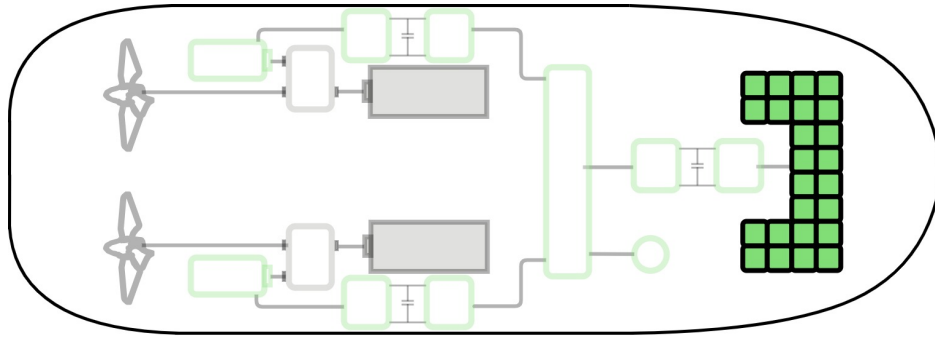


Figura 1.5: BattBank in power train.

Tabla 1.2: Valores de los parámetros del modelo Batt Bank

Parámetro	Shepherd values
N_s	19 [-]
N_p	85 [-]
A	27.36 [V]
B	0.0353 [Ah^{-1}]
K	0.0011 [V]
V_0	745.7320 [V]

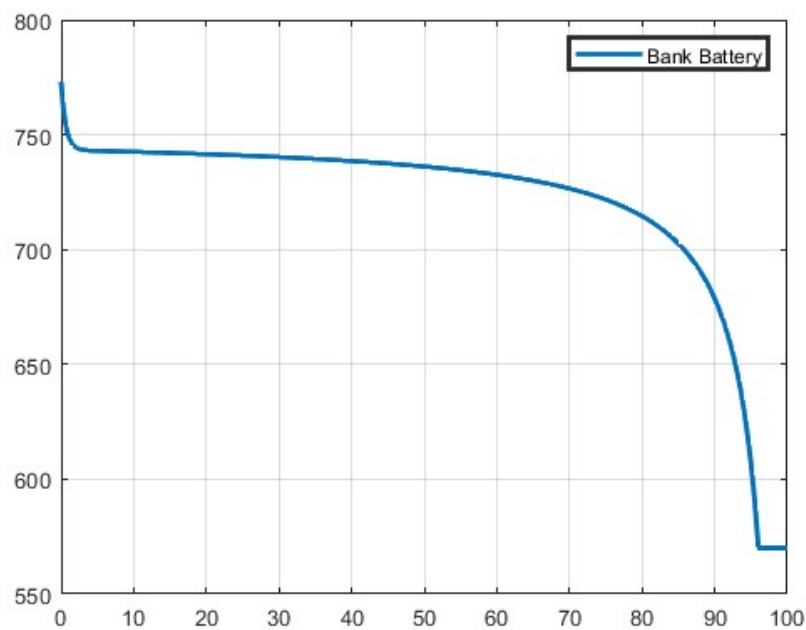


Figura 1.6: BattBank voltage profile.

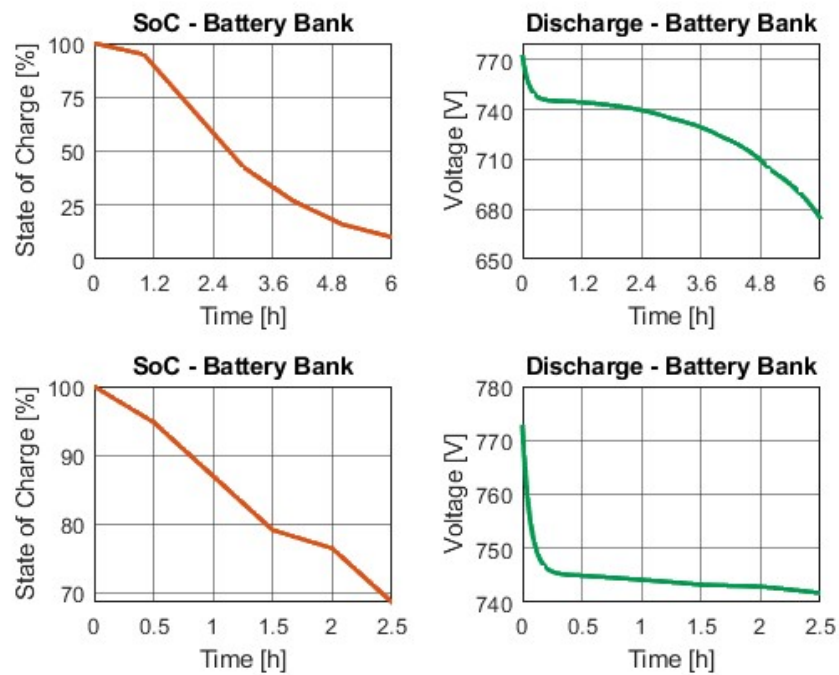


Figura 1.7: BattBank Electrical behavior.

1.3. Power Converter Battery

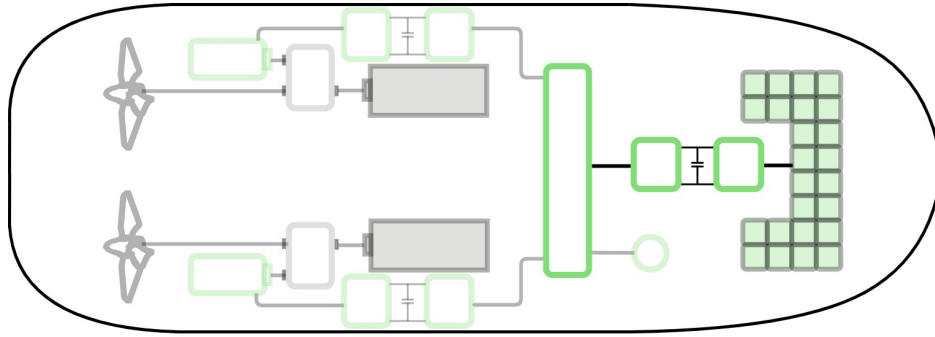


Figura 1.8: Power Converter Bank.

1.4. Electric Motor

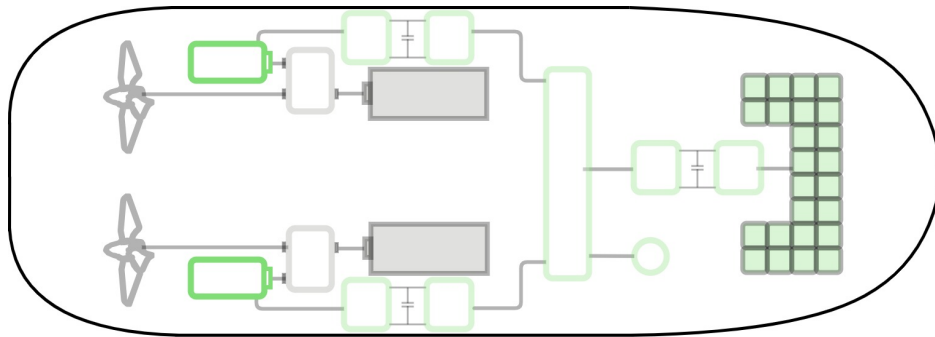


Figura 1.9: ElectricMotor in power train.

1.5. Diesel Propulsion Engine

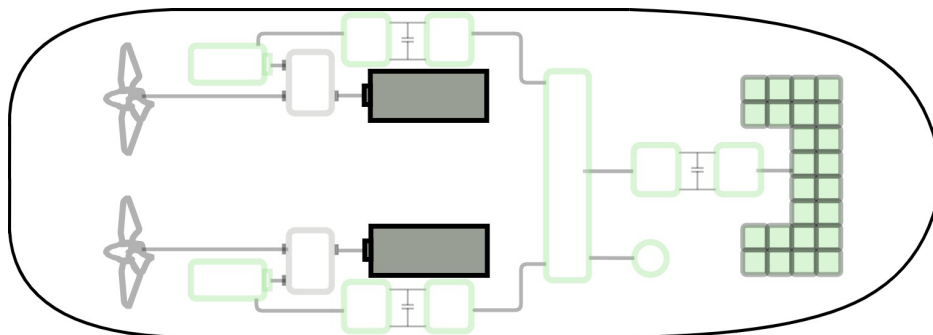


Figura 1.10: Diesel Propulsion Engine in power train.

1.6. Propeller

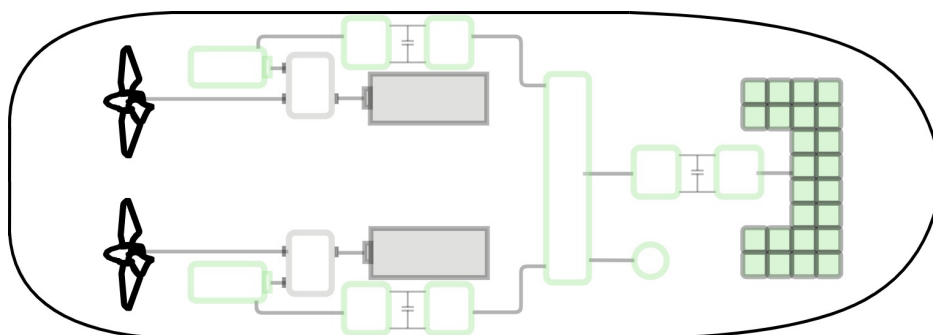


Figura 1.11: Propeller in power train.

- Explicación - Curva hélice - Simulaciones de Potencia

Bibliografía

- [1] A. Carreno, M. Malinowski, M. A. Perez, and J. Ding, "Effects of grid voltage and load unbalances on the efficiency of a hybrid distribution transformer," *IEEE Open Journal of the Industrial Electronics Society*, vol. 5, pp. 1206–1220, 2024.
- [2] J. Yin, N. Dai, S. Vazquez, M. A. Perez, B. Zhang, J. I. Leon, and L. G. Franquelo, "Direct pulsewidth modulation technique for modular multilevel converters based on full-bridge submodules," *IEEE Transactions on Power Electronics*, pp. 1–14, 2024.
- [3] J. Yin, N. Dai, J. I. Leon, M. A. Perez, S. Vazquez, and L. G. Franquelo, "Common-mode-voltage regulation of modular multilevel converters through model predictive control," *IEEE Transactions on Power Electronics*, vol. 39, no. 6, pp. 7167–7180, 2024.
- [4] A. Carreno, M. Malinowski, M. A. Perez, and C. R. Baier, "Circulating active power flow analysis in a hybrid transformer with the series converter connected to the primary side," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 10, pp. 11 775–11 784, 2024.
- [5] J. Yin, N. Dai, S. Vazquez, A. Marquez, J. I. Leon, M. A. Perez, and L. G. Franquelo, "An improved indirect pulsewidth modulation technique for modular multilevel converters," *IEEE Transactions on Power Electronics*, vol. 39, no. 1, pp. 733–743, 2024.
- [6] A. Carreno, M. A. Perez, and M. Malinowski, "State-feedback control of a hybrid distribution transformer for power quality improvement of a distribution grid," *IEEE Transactions on Industrial Electronics*, vol. 71, no. 2, pp. 1147–1157, 2024.
- [7] D. S. D'antonio, O. López-Santos, A. Navas-Fonseca, F. Flores-Bahamonde, and M. A. Pérez, "Multi-mode master-slave control approach for more modular and reconfigurable hybrid microgrids," *IEEE Access*, vol. 11, pp. 55 334–55 348, 2023.
- [8] C. R. Baier, F. A. Villarroel, M. A. Torres, M. A. Pérez, J. C. Hernández, and E. E. Espinosa, "A predictive control scheme for a single-phase grid-supporting quasi-z-source inverter and its integration with a frequency support strategy," *IEEE Access*, vol. 11, pp. 5337–5351, 2023.
- [9] J. Samanes, L. Rosado, E. Gubia, J. Lopez, and M. A. Perez, "Deadbeat voltage control for a grid-forming power converter with lcl filter," *IEEE Transactions on Industry Applications*, vol. 59, no. 2, pp. 2473–2482, 2023.
- [10] M. Liserre, M. A. Perez, M. Langwasser, C. A. Rojas, and Z. Zhou, "Unlocking the hidden capacity of the electrical grid through smart transformer and smart transmission," *Proceedings of the IEEE*, vol. 111, no. 4, pp. 421–437, 2023.

- [11] F. A. Villarroel, J. R. Espinoza, M. A. Pérez, C. R. Baier, J. A. Rohten, R. O. Ramírez, E. S. Pulido, and J. J. Silva, "A predictive shortest-horizon voltage control algorithm for non-minimum phase three-phase rectifiers," *IEEE Access*, vol. 10, pp. 107 598–107 615, 2022.
- [12] M. A. Perez, S. Ceballos, G. Konstantinou, J. Pou, and R. P. Aguilera, "Modular multilevel converters: Recent achievements and challenges," *IEEE Open Journal of the Industrial Electronics Society*, vol. 2, pp. 224–239, 2021.
- [13] F. A. Villarroel, J. R. Espinoza, M. A. Pérez, R. O. Ramírez, C. R. Baier, D. Sbárbaro, J. J. Silva, and M. A. Reyes, "Stable shortest horizon fcs-mpc output voltage control in non-minimum phase boost-type converters based on input-state linearization," *IEEE Transactions on Energy Conversion*, vol. 36, no. 2, pp. 1378–1391, 2021.
- [14] J. Yin, J. I. Leon, M. A. Perez, L. G. Franquelo, A. Marquez, and S. Vazquez, "Model predictive control of modular multilevel converters using quadratic programming," *IEEE Transactions on Power Electronics*, vol. 36, no. 6, pp. 7012–7025, 2021.
- [15] J. Yin, J. I. Leon, M. A. Perez, L. G. Franquelo, A. Marquez, B. Li, and S. Vazquez, "Variable rounding level control method for modular multilevel converters," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 4791–4801, 2021.
- [16] C. A. Reusser, H. A. Young, J. R. Perez Osses, M. A. Perez, and O. J. Simmonds, "Power electronics and drives: Applications to modern ship propulsion systems," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 106–122, 2020.
- [17] F. Ruiz, M. A. Perez, J. R. Espinosa, T. Gajowik, S. Stynski, and M. Malinowski, "Surveying solid-state transformer structures and controls: Providing highly efficient and controllable power flow in distribution grids," *IEEE Industrial Electronics Magazine*, vol. 14, no. 1, pp. 56–70, 2020.
- [18] Q. Yang, M. Saeedifard, and M. A. Perez, "Sliding mode control of the modular multilevel converter," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 887–897, 2019.
- [19] C. A. Rojas, S. Kouro, M. A. Perez, and J. Echeverria, "Dc–dc mmc for hvdc grid interface of utility-scale photovoltaic conversion systems," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 352–362, 2018.
- [20] A. Dekka, B. Wu, R. L. Fuentes, M. Perez, and N. R. Zargari, "Evolution of topologies, modeling, control schemes, and applications of modular multilevel converters," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 4, pp. 1631–1656, 2017.
- [21] O. Menendez, F. A. Auat Cheein, M. Perez, and S. Kouro, "Robotics in power systems: Enabling a more reliable and safe grid," *IEEE Industrial Electronics Magazine*, vol. 11, no. 2, pp. 22–34, 2017.
- [22] A. Dekka, B. Wu, R. L. Fuentes, M. Perez, and N. R. Zargari, "Voltage-balancing approach with improved harmonic performance for modular multilevel converters," *IEEE Transactions on Power Electronics*, vol. 32, no. 8, pp. 5878–5884, 2017.
- [23] C. D. Fuentes, C. A. Rojas, H. Renaudineau, S. Kouro, M. A. Perez, and T. Meynard, "Experimental validation of a single dc bus cascaded h-bridge multilevel inverter for multistring photovoltaic systems," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 930–934, 2017.