MINISTERUL EDUCAŢIEI ŞI CERCETĂRII
AL REPUBLICII MOLDOVA

Universitatea Tehnică a Moldovei

Facultatea Energetică şi Inginerie Electrică

Departamentul Energetică

Admis la susţinere

Şef departament:

HLUSOV Viorica, conf. univ., dr.

„ ____”_____ 2024

Dimensionarea unui sistem de stocare a energiei electrice integrat în retelele electrice de distributie

Teză de master

Student: _____ **CIBOTARI Danu**, gr. EM-22M

Conducător: _____ **TÎRŞU Mihai**, conf. cercet., dr.

Chişinău, 2024

ADNOTARE

Autor – CIBOTARI Danu. **Titlul –** *Dimensionarea unui sistem de stocare a energiei electrice integrat în retelele electrice de distributie*

Structura lucrării: lucrarea conține o introducere, cinci capitole, concluzii, bibliografie din 139 titluri, 90 pagini, 52 figuri, 6 tabele.

Cuvinte-cheie: Sistem de stocare, baterie, stabilitate sistem, DC-AC, AC-DC.

Scopul lucrării: Această lucrare sa concentrat pe diferitele aspecte ale integrării a sistemelor de stocare a energiei în reţelele de distribuţie. S-a demonstrat că sistemul de stocare are potențialul pentru a consolida și îmbunătăți rețeaua electrică în mai multe aspecte.

Obiectivele generale: Prezentarea în masă a informațiilor cu atitudini generali , privind sistemele de stocare și inter-conexiunile cu sistemul.

Rezultate obținute: Sunt prezentate exemplul de calcul pentru găsirea nodului optim de a fi instalat sistemul de stocare. Desigur au fost prezentate graficile obținute în urma simulării sistemului pe baterii, conectat la sistem.

ABSTRACT

Author –CIBOTARI Danu. **Title –**. Dimensioning of an electrical energy storage system integrated in electrical distribution networks

Thesis structure: The work contains an introduction, five chapters, conclusions, bibliography of 139 titles, 90 pages, 52 figures, 6 tables.

Keywords: Storage system, battery, system stability, DC-AC, AC-DC.

The scope of the work: This paper focused on the various aspects of the integration of energy storage systems in distribution networks. The storage system has been shown to have the potential to strengthen and improve the power grid in several aspects.

General objectives: Mass presentation of information with general attitudes, regarding storage systems and system interconnections.

Result obtained: The calculation example for finding the optimal node to install the storage system is presented. Of course, the graphics obtained from the simulation of the system on batteries, connected to the system, were presented.

CUPRINS

INTRODUCERE

În era actuală a energiei, în care surselor regenerabile devin din ce în ce mai prelevante și necesitatea unei distribuții eficiente și fiabile a energiei electrice este tot mai stringentă, conceptul de "Proiectarea unui Sistem de Stocare a Energiei Electrice Integrat în Rețelele Electrice de Distribuție" capătă o importanță semnificativă. Acest proiect reprezintă un pas esențial în evoluția și optimizarea infrastructurii energetice, adaptându-se cerințelor unei lumi în transformare rapidă.

Sistemele de stocare a energiei au devenit un element central în dezvoltarea rețelelor electrice inteligente și în eforturile de a integra în mod eficient sursele de energie regenerabilă, precum energia solară și cea eoliană. Într-un context în care variabilitatea producției de energie din surse regenerabile poate pune presiune asupra stabilității rețelelor de distribuție, un sistem de stocare adecvat devine cheia pentru echilibrarea ofertei și cererii de energie electrică, pentru reducerea pierderilor și pentru gestionarea vârfurilor de consum.

Această inițiativă nu doar abordează provocările tehnice ale proiectării unui astfel de sistem complex, ci și aduce în prim-plan aspecte cruciale legate de sustenabilitate, economie și adaptabilitate la schimbările climatice. Într-o lume în care resursele energetice tradiționale sunt din ce în ce mai limitate, dezvoltarea unui sistem de stocare a energiei în rețelele de distribuție poate contribui semnificativ la reducerea emisiilor de gaze cu efect de seră și la asigurarea unei aprovizionări energetice fiabile pentru generațiile viitoare.

În această lucrare, vom explora detaliat aspectele cheie legate de proiectarea și implementarea unui sistem de stocare a energiei electrice în rețelele de distribuție, de la selectarea tehnologiilor potrivite până la integrarea lor în infrastructura existentă. Vom examina, de asemenea, beneficiile semnificative pe care le poate aduce această inițiativă, contribuind la transformarea rețelelor electrice tradiționale în rețele inteligente și sustenabile, adaptate nevoilor viitorului.

BIBLIOGRAFIE

[1] K. Clement, E. Haesen, and J. Driesen, "Stochastic analysis of the impact of plug-in hybrid electric vehicles on the distribution grid," in *Proc. CIRED 20th Int. Conf. Exhib. Electric. Distribution - Part 2*,
2009, pp. 1–4.

[2] R. A. Walling, R. Saint, R. C. Dugan, J. Burke, and L. A. Kojovic, "Summary of distributed resources impact on power delivery systems," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1636–1644, Jul. 2008.

[3] J. Delgado, R. Faria, P. Moura, and A. T. de Almeida, "Impacts of plug-in electric vehicles in the portuguese electrical grid," *Transp. Res. Part D Transport Environ.*, vol. 62, pp. 372–385, Jul. 2018.

[4] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, "Evaluating distributed generation impacts with a multiobjective index," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1452–1458, Jul. 2006.

[5] A. Canova, L. Giaccone, F. Spertino, and M. Tartaglia, "Electrical impact of photovoltaic plant in distributed network," *IEEE Trans. Ind.*
Appl., vol. 45, no. 1, pp. 341–347, Jan./Feb. 2009.

[6] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality," *Renewable Sustain. Energy Rev.*, vol. 91, pp. 1205–1230, Aug. 2018.

[7] G. Castagneto Gissey, P. E. Dodds, and J. Radcliffe, "Market and regulatory barriers to electrical energy storage innovation," *Renewable Sustain. Energy Rev.*, vol. 82, pp. 781–790, Feb. 2018.

[8] S. Mir Mohammadi Kooshknow and C. Davis, "Business models design space for electricity storage systems: Case study of the Netherlands," *J. Energy Storage*, vol. 20, pp. 590–604, Dec. 2018.

[9] K. K. Zame, C. A. Brehm, A. T. Nitica, C. L. Richard, and G. D. Schweitzer, "Smart grid and energy storage: Policy recommendations," *Renewable Sustain. Energy Rev.*, vol. 82, pp. 1646–1654, Feb. 2018.

[10] G. Zubi, R. Dufo-López, M. Carvalho, and G. Pasaoglu, "The lithiumion battery: State of the art and future perspectives," *Renewable Sustain. Energy Rev.*, vol. 89, pp. 292–308, Jun. 2018.

[11] E. Telaretti and L. Dusonchet, "Stationary battery technologies in the U.S.: Development Trends and prospects," *Renewable Sustain. Energy Rev.*, vol. 75, pp. 380–392, Aug. 2017.

[12] A. B. Gallo, J. R. Simões-moreira, H. K. M. Costa, M. M. Santos, and E. Moutinho, "Energy storage in the energy transition context: A technology review," *Renewable Sustain. Energy Rev.*, vol. 65, pp. 800– 822, Nov. 2016.

[13] S. Sabihuddin, A. E. Kiprakis, and M. Mueller, "A numerical and graphical review of energy storage technologies," *Energies*, vol. 8, no. 1, pp. 172–216, 2015.

[14] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renewable Sustain. Energy Rev.*, vol. 8, no. 1, pp. 172–216, 2015.

[15] M. C. Argyrou, P. Christodoulides, and S. A. Kalogirou, "Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications," *Renewable Sustain. Energy Rev.*, vol. 94, pp. 804–821, Oct. 2018.

[16] N. D. Hatziargyriou, D. Škrlec, T. Capuder, P. S. Georgilakis, and M. Zidar, "Review of energy storage allocation in power distribution networks: Applications, methods and future research," *IET Gener. Transmiss. Distrib.*, vol. 10, no. 3, pp. 645–652, 2016.

[17] Y. Yang, S. Bremner, C. Menictas, and M. Kay, "Battery energy storage system size determination in renewable energy systems: A review," *Renewable Sustain. Energy Rev.*, vol. 91, pp. 109–125, 2018.

[18] H. Saboori, R. Hemmati, S. M. S. Ghiasi, and S. Dehghan, "Energy storage planning in electric power distribution networks—A state-ofthe- art review," *Renewable Sustain. Energy Rev.*, vol. 79(C), pp. 1108– 1121, 2017.

[19] I. Alsaidan, A. Alanazi, W. Gao, H. Wu, and A. Khodaei, "Stateof- the-art in microgrid-integrated distributed energy storage sizing,"

[20] L. A. Wong, V. K. Ramachandaramurthy, P. Taylor, J. B. Ekanayake,

[21] V. Fernão Pires, E. Romero-Cadaval, D. Vinnikov, I. Roasto, and J. F. Martins, "Power converter interfaces for electrochemical energy storage systems—A review," *Energy Convers. Manage.*, vol. 86, pp. 453– 475, 2014.

[22] G. Wang *et al.*, "A review of power electronics for grid connection of utility-scale battery energy storage systems," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1778–1790, Oct. 2016.

[23] World Energy Council, "World energy resources 2016," Tech. Rep., London, U.K., 2016.

[24] IRENA, Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi, 2017.

[25] E. Chemali, M. Preindl, P. Malysz, and A. Emadi, "Electrochemical and electrostatic energy storage and management systems for electric drive vehicles: State-of-the-art review and future trends," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 4, no. 3, pp. 1117–1134,
Sep. 2016.

[26] BloombergNEF, Mar. 5, 2019. [Online]. Available: https://about.bnef. com/blog/behind-scenes-take-lithium-ion-battery-prices/

[27] BloombergNEF, Dec. 3, 2019. [Online]. Available: https: //about.bnef.com/blog/battery-pack-prices-fall-as-market-rampsup- with-market-average-at-156-kwh-in-2019/

[28] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Appl. Energy*, vol. 137, pp. 511–536, Jan. 2015.

[29] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Prog. Nat. Sci.*, vol. 19, no. 3, pp. 291–312, 2009.

[30] H. Ibrahim, A. Ilinca, and J. Perron, "Energy storage systems- Characteristics and comparisons," *Renewable Sustain. Energy Rev.*, vol. 12, no. 5, pp. 1221–1250, 2008.

[31] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renewable Sustain. Energy Rev.*, vol. 13, no. 6-7, pp. 1513– 1522, 2009.

[32] Q. Liao, B. Sun, Y. Liu, J. Sun, and G. Zhou, "A techno-economic analysis on NaS battery energy storage system supporting peak shaving," *Int. J. Energy Res.*, vol. 40, pp. 241–247, 2016.

[33] N. Kawakami *et al.*, "Development and field experiences of stabilization system using 34MW NAS batteries for a 51MW Wind farm," in *Proc. IEEE Int. Symp. Ind. Electron.*, 2010, pp. 2371–2376.

[34] S. Tewari and N. Mohan, "Value of NAS energy storage toward integrating wind: Results from the wind to battery project," *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 532–541, Feb. 2013.

[35] L. N. Thaller, "Electrically rechargeable redox flow cells," in *Proc. 9th Intersociety Energy Convers. Eng. Conf.*, 1974, pp. 1–5.

[36] P. Leung *et al.*, "Recent developments in organic redox flow batteries: A critical review," *J. Power Sources*, vol. 360, pp. 243–283, 2017.

[37] C. Ponce de León, A. Frías-Ferrer, J. González-García, D. A. Szánto, and F. C. Walsh, "Redox flow cells for energy conversion," *J. Power Sources*, vol. 160, no. 1, pp. 716–732, 2006.

[38] P. Leung, X. Li, C. Ponce De León, L. Berlouis, C. T. Low, and F. C. Walsh, "Progress in redox flow batteries, remaining challenges and their applications in energy storage," *RSC Adv.*, vol. 2, no. 27, pp. 10125–10156, 2012.

[39] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical energy storage for the grid : A battery of choices," *Science*, vol. 334, no. 6058, pp. 928–935 2011.

[40] BYD, "B-Box BYD," 2018. [Online]. Available: https://en.byd.com/ energy/b-box-ess/

[41] B. Diouf and R. Pode, "Potential of lithium-ion batteries in renewable energy," *Renewable Energy*, vol. 76, pp. 375–380, 2015.

[42] M. Aneke and M. Wang, "Energy storage technologies and real life applications - A state of the art review," *Appl. Energy*, vol. 179, pp. 350–377, 2016.

[43] A. I. Stan, M. Swierczynski, D. I. Stroe, R. Teodorescu, and S. J. Andreasen, "Lithium ion battery chemistries from renewable energy storage to automotive and back-up power applications—An overview," in *Proc. Int. Conf. Optim. Elect. Electron. Equipment*, 2014, pp. 713–720.

[44] T. Zhao, "Sustainable development strategy for EV battery," 2018, pp. 1–31. [Online]. Available: https://www.iea.org/media/Workshops

45] I. Tsiropoulos, D. Tarvydas, and N. Lebedeva, "Li-ion batteries for mobility and stationary storage applications—Scenarios for costs and market growth," Publications Office of the European Union, Luxembourg, Tech. Rep., 2018.

[46] I. Trintis, S. Munk-Nielsen, and R. Teodorescu, "Cascaded H-bridge with bidirectional boost converters for energy storage," in *Proc. 14th Eur. Conf. Power Electron. Appl.*, 2011, pp. 1–9.

[47] "IEC Standard Voltages," IEC Standard 60038:2009, Jun. 2009.

[48] M. Liu,W. Li, C.Wang, M. P. Polis, L. Y.Wang, and J. Li, "Reliability evaluation of large scale battery energy storage systems," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2733–2743, Nov. 2017.

[49] IEEE Standards Association, "IEEE recommended practice and requirements for harmonic control in electric power systems," IEEE Standard 519-2014, 2014.

[50] IEEE Standards Association, "IEEE Standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces," IEEE Standard 1547-2018, 2018, pp. 1– 138.

[51] S. Vazquez, S. M. Lukic, E. Galvan, L. G. Franquelo, and J. M. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 3881–3895, Dec. 2010.

[52] J. I. Y. Ota, T. Sato, and H. Akagi, "Enhancement of performance, availability, and flexibility of a battery energy storage system based on a modular multilevel cascaded converter (MMCC-SSBC)," *IEEE Trans. Power Electron.*, vol. 31, no. 4, pp. 2791–2799, Apr. 2016.

[53] "Semikron," 2020. [Online]. Available: https://www.semikron.com/ products/product-classes/igbt-modules.html

[54] P. D. Judge and T. C. Green, "Modular multilevel converter with partially rated integrated energy storage suitable for frequency support and ancillary service provision," *IEEE Trans. Power Del.*, vol. 34, no. 1, pp. 208–219, Feb. 2019.

[55] A. Hillers and J. Biela, “Optimal design of the modular multilevel converter for an energy storage system based on split batteries,” in *Proc. 15th Eur. Conf. Power Electron. Appl. EPE*, 2013, pp. 1–11.

[56] L. Baruschka and A. Mertens, “Comparison of cascaded H-bridge and modular multilevel converters for BESS application,” in *Proc. IEEE Energy Convers. Congr. Expo. Energy Convers. Innov. Clean Energy Future*, 2011, pp. 909–916.

[57] H. C. Hesse, M. Schimpe, D. Kucevic, and A. Jossen, “Lithium-ion battery storage for the grid—A review of stationary battery storage system design tailored for applications in modern power grids,” *Energies*, vol. 10, no. 12, p. 2107, 2017.

[58] S. Bhim, K. Al-Haddad, and A. Chandra, “Harmonic elimination, reactive power compensation an load balancing in three-phase, fourwire electric distribution systems supplying non-linear loads,” *Electric Power Syst. Res.*, vol. 44, pp. 93–100, 1998.

[59] X. Liang, “Emerging power quality challenges due to integration of renewable energy sources,” *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 855–866, Mar./Apr. 2017.

[60] T. N. Reddy, M. K. Mishra, and S. Srinivas, “Grid interactive combined supercapacitor/battery energy storage system with power quality features,” in *Proc. IEEE Int. Conf. Ind. Technol.*, 2015, pp. 2600–2605.

[61] H. Lee, B. Y. Shin, S. Han, S. Jung, B. Park, and G. Jang, “Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications,” *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012, Art. no. 5701904.

[62] Z. Zhang, Y. Zhang, Q. Huang, and W.-J. Lee, “Market-oriented optimal dispatching strategy for a wind farm with a multiple stage hybrid energy storage system,” *CSEE J. Power Energy Syst.*, vol. 4, no. 4,

[67] W. R. Issa, M. A. Abusara, and S. M. Sharkh, “Control of transient power during unintentional islanding of microgrids,” *IEEE Trans. Power Electron.*, vol. 30, no. 8, pp. 4573–4584, Aug. 2015.

[68] S. D. Izadkhast, “Aggregation of plug-in electric vehicles in power systems for primary frequency control,” Ph.D. dissertation, Inst. Res. Technol., Comillas Pontifical Univ., Madrid, Spain, 2017.

[69] IEEE PES Distribution Systems Analysis Subcommittee Radial Test Feeders, “IEEE European LV Test Feeder,” 2015, pp. 1–6. [Online]. Available: https://site.ieee.org/pes-testfeeders/resources/

[70] N. Mahmud and A. Zahedi, “Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation,” *Renewable Sustain. Energy Rev.*, vol. 64, pp. 582–595, 2016.

[71] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, "Distributed and decentralized voltage control of smart distribution networks," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2999–3008, Nov. 2017.

[72] P.Wang, D. H. Liang, J. Yi, P. F. Lyons, P. J. Davison, and P. C. Taylor, "Integrating electrical energy storage into coordinated voltage control schemes for distribution networks," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1018–1032, Mar. 2014.

[73] C. Sabillon-Antunez, O. D. Melgar-Dominguez, J. F. Franco, M. Lavorato, and M. J. Rider, "Volt-VAr control and energy storage device operation to improve the electric vehicle charging coordination in unbalanced distribution networks," *IEEE Trans. Sustain. Energy*, vol. 8, no. 4, pp. 1560–1570, Oct. 2017.

[74] CEI - Comitato Elettrotecnico Italiano, "CEI 0-16," 2019. [Online]. Available: https://www.ceinorme.it/it/norme-cei-0-16-e-0-21.html

[75] C. C. E. Italiano, "CEI 0-21," 2019. [Online]. Available: https://www.ceinorme.it/it/norme-cei-0-16-e-0-21.html

[76] "Connection and operation to medium-voltage grid," 2018. [Online]. Available: VDE-AR-N 4110

[77] "Technical requirements for the connection to and parallel operation with low-voltage distribution networks," 2018. [Online]. Available: VDE-AR-N 4105

[78] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A survey of frequency and voltage control ancillary services—Part I: Technical features," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 350– 357, Feb. 2007.

[79] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A survey of frequency and voltage control ancillary services—Part II: Economic features," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 358– 366, Feb. 2007.

[80] "TenneT B.V," 2020. [Online]. Available: https://www.tennet.eu/ electricity-market/ancillary-services/fcr-documen ts/

[81] "Elia Group," 2020. [Online]. Available: https://www.elia.be/en/griddata/ balancing

[82] "Rede Eléctrica de España," 2020. [Online]. Available: https://www.ree.es/es/actividades/operacion-del-sistemaelectrico/ procedimientos-de-operaciong

[83] Réseau de Transport d'Électricité, "Frequency ancillary services terms and conditions," 2018. [Online]. Availacble: http: //clients.rte france.com/lang/an/clients_producteurs/services_clients/ services_systeme.jsp

[84] A. Rahimi, M. Zarghami, M. Vaziri, and S. Vadhva, "A simple and effective approach for peak load shaving using Battery Storage Systems,"in *Proc. 45th North Am. Power Symp.*, 2013, pp. 1–5.

[85] A. J. Pimm, T. T. Cockerill, and P. G. Taylor, “The potential for peak shaving on low voltage distribution networks using electricity storage

[86] M. Farrokhifar, S. Grillo, and E. Tironi, “Loss minimization in medium voltage distribution grids by optimal management of energy storage devices,” in *Proc. IEEE PowerTech Grenoble Conf.*, 2013, pp. 1–5.

[87] A. Nourai, V. I. Kogan, and C. M. Schafer, “Load leveling reduces T&D line losses,” *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2168– 2173, Oct. 2008.

[88] A. Oudalov, D. Chartouni, and C. Ohler, “Optimizing a battery energy storage system for primary frequency control,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1259–1266, Aug. 2007.

[89] P. Mercier, R. Cherkaoui, and A. Oudalov, “Optimizing a battery energy storage system for frequency control application in an isolated grids,” *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 985–995, Jun. 2013.

[90] D.-I. Stroe, V. Knap,M. Swierczynski, A.-I. Stroe, and R. Teodorescu, “Operation of a grid-connected lithium-ion battery energy storage system for primary frequency regulation: A battery lifetime perspective,” *IEEE Trans. Ind. Appl.*, vol. 53, no. 1, pp. 430–438, Jan./Feb. 2017.

[91] A. Daggett, M. Qadrdan, and N. Jenkins, “Feasibility of a battery storage system for a renewable energy park operating with price arbitrage,” in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. Eur. ISGT-Europe*, 2018, pp. 1–6.

[92] B. Zakeri, S. Syri, and F. Wagner, “Economics of energy storage in the German electricity and reserve markets,” in *Proc. Int. Conf. Eur. Energy Markets*, 2017, pp. 1–6.

[93] “Gestore dei Mercati Energetici S.p.A,” 2020. [Online]. Available: https://www.mercatoelettrico.org/It/Statistiche/ME/DatiSintesi.aspx

[94] “Nord Pool AS,” 2019, [Online]. Available: https://www.nordpoolgroup.com/historical-market-data/

[95] J. M. Gantz, S. M. Amin, and A. M. Giacomoni, “Optimal capacity partitioning of multi-use customer-premise energy storage systems,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1292–1299, May 2014.

[96] A. Perez, R. Moreno, R. Moreira, M. Orchard, and G. Strbac, “Effect of battery degradation on multi-service portfolios of energy storage,” *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1718–1729, Oct. 2016.

[97] R. Moreno, R. Moreira, and G. Strbac, “A MILP model for optimising multi-service portfolios of distributed energy storage,” *Appl. Energy*, vol. 137, pp. 554–566, 2015.

[98] D. Pudjianto, M. Aunedi, P. Djapic, and G. Strbac, “Whole-systems assessment of the value of energy storage in low-carbon electricity systems,” *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1098–1109, Mar. 2014.

[99] J. Kennedy and R. Eberhart, “Particle swarm optimization,” in *Proc. IEEE Int. Conf. Neural Networks*, vol. 4, 1995, pp. 1–7.

[100] J. H. Holland, *Adaptation in Natural and Artificial Systems*. Cambridge, MA, USA: MIT Press, 1992.

[101] A. Paffrath, M. Henneberger, and J. Mayer, “Particle swarm optimization: Basic concepts, variants and applications in power systems,” *IEEE Trans. Evol. Comput.*, vol. 12, no. 2, pp. 171–195, Apr. 2008.

[102] A. Vieira Pombo, J. Murta-Pina, and V. Fernão Pires, “Multiobjective formulation of the integration of storage systems within distribution networks for improving reliability,” *Electric Power Syst. Res.*, vol. 148, pp. 87–96, 2017.

[103] S. W. Alnaser and L. F. Ochoa, “Optimal sizing and control of energy storage in wind power-rich distribution networks,” *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2004–2013, May 2016.

[104] R. Hemmati, H. Saboori, and M. A. Jirdehi, “Stochastic planning and scheduling of energy storage systems for congestion management in electric power systems including renewable energy resources,” *Energy*, vol. 133, pp. 380–387, Aug. 2017.

[105] A. S. Awad, T. H. EL-Fouly, and M. M. Salama, “Optimal ESS allocation for benefit maximization in distribution networks,” *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1668–1678, Jul. 2017.

[106] E. Grover-Silva, R. Girard, and G. Kariniotakis, “Optimal sizing and placement of distribution grid connected battery systems through an SOCP optimal power flow algorithm,” *Appl. Energy*, vol. 219, pp. 385– 393, 2018.

[107] K. Mahani, F. Farzan, and M. A. Jafari, “Network-aware approach for energy storage planning and control in the network with high penetration of renewables,” *Appl. Energy*, vol. 195, pp. 974–990, 2017.

[108] M. R. Jannesar, A. Sedighi, M. Savaghebi, and J. M. Guerrero, “Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovoltaic penetration,” *Appl. Energy*, vol. 226, pp. 957–966, 2018.

[109] M. Nick, R. Cherkaoui, and M. Paolone, “Optimal siting and sizing of distributed energy storage systems via alternating direction method of multipliers,” *Int. J. Elect. Power Energy Syst.*, vol. 72, pp. 33–39, 2015.

[110] H. Akhavan-Hejazi and H. Mohsenian-Rad, “Energy storage planning in active distribution grids: A chance-constrained optimization with non-parametric probability functions,” *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1972–1985, May 2018.

[111] G. Carpinelli, G. Celli, S. Mocci, F. Mottola, F. Pilo, and D. Proto,

[112] A. Giannitrapani, S. Paoletti, A. Vicino, and D. Zarrilli, "Optimal allocation of energy storage systems for voltage control in LV distribution networks," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2859–2870, Nov. 2017.

[113] P. Lazzeroni and M. Repetto, "Optimal planning of battery systems for power losses reduction in distribution grids," *Electric Power Syst. Res.*, vol. 167, pp. 94–112, 2019.

[114] M. Nick, R. Cherkaoui, and M. Paolone, "Optimal planning of distributed energy storage systems in active distribution networks embedding grid reconfiguration," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1577–1590, Mar. 2018.

[115] A. R. Camargo, C. A. Castro, and M. Lavorato, "Optimal allocation of energy storage devices in distribution systems considering lifetime characteristics of batteries," in *Proc. IEEE Int. Conf. Power Syst. Technol.*, 2016, pp. 1–6.

[116] S. B. Karanki, D. Xu, B. Venkatesh, and B. N. Singh, "Optimal location of battery energy storage systems in power distribution network for integrating renewable energy sources," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2013, pp. 4553–4558.

[117] M. Sedghi, M. Aliakbar-Golkar, and M. R. Haghifam, "Distribution network expansion considering distributed generation and storage units using modified PSO algorithm," *Int. J. Elect. Power Energy Syst.*, vol. 52, no. 1, pp. 221–230, 2013.

[118] K. K. Mehmood, S. U. Khan, S.-J. Lee, Z. M. Haider, M. K. Rafique, and C.-H. Kim, "Optimal sizing and allocation of battery energy storage systems with wind and solar power DGs in a distribution network for voltage regulation considering the lifespan of batteries," *IET Renewable Power Gener.*, vol. 11, no. 10, pp. 1305–1315, 2017.

[119] A. F. Crossland, D. Jones, and N. S. Wade, "Planning the location and rating of distributed energy storage in LV networks using a genetic algorithm with simulated annealing," *Int. J. Elect. Power Energy Syst.*, vol. 59, pp. 103–110, 2014.

[120] C. Brivio, "Battery energy storage systems: Modelling, applications and design criteria," Ph.D. dissertation, Politecnico di Milano, Milan, Italy, 2012. [Online]. Available: http://hdl.handle.net/10589/136844

[121] H. H. Eldeeb, S. Faddel, and O. A. Mohammed, "Multi-objective optimization technique for the operation of grid tied PV powered EV charging station," *Electric Power Syst. Res.*, vol. 164, pp. 201–211, 2018.

[122] R. C. Dugan, J. A. Taylor, and D. Montenegro, "Energy storage modelling for distribution planning," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 954–962, Mar./Apr. 2017.

[123] M. Dubarry and A. Devie, "Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging," *J. Energy Storage*, vol. 18, pp. 185–195, 2018.

[124] M. T. Lawder *et al.*, "Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications," *Proc. IEEE*, vol. 102, no. 6, pp. 1014–1030, Jun. 2014.

[125] R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala, and I. Gyuk, "Energy management and optimization methods for grid energy storage systems," *IEEE Access*, vol. 6, pp. 13231–13260, 2017.

[126] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems*. Hoboken, NJ, USA: Wiley, 2010.

[127] L. Wang, D. H. Liang, A. F. Crossland, P. C. Taylor, D. Jones, and N. S. Wade, "Coordination of multiple energy storage units in a lowvoltage distribution network," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2906–2918, Nov. 2015.

[128] S. Hashemi and J. Østergaard, "Efficient control of energy storage for increasing the PV hosting capacity of LV grids," *IEEE Trans. Smar* generation,energy storage, and active loads," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2499–2508, Apr. 2015.

[129] K. Christakou, D. C. Tomozei, M. Bahramipanah, J. Y. Le Boudec, and M. Paolone, "Primary voltage control in active distribution networks via broadcast signals: The case of distributed storage," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2314–2325, Sep. 2014.

[130] D. Zarrilli, A. Giannitrapani, S. Paoletti, and A. Vicino, "Energy storage operation for voltage control in distribution networks: A receding horizon approach," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 2,

[131] Y. Wang, K. T. Tan, X. Y. Peng, and P. L. So, "Coordinated control of distributed energy-storage systems for voltage regulation in distribution networks," *IEEE Trans. Power Del.*, vol. 31, no. 3, pp. 1132–1141, Jun. 2016.

[132] J. Von Appen, T. Stetz, M. Braun, and A. Schmiegel, "Local voltage control strategies for PV storage systems in distribution grids," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 1002–1009, Mar. 2014.

[133] S. J. Lee *et al.*, "Coordinated control algorithm for distributed battery energy storage systems for mitigating voltage and frequency deviations," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1713–1722, May 2016

[134] M. Zeraati, M. E. Hamedani Golshan, and J.M. Guerrero, "Distributed control of battery energy storage systems for voltage regulation in distribution networks with high PV penetration," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3582–3593, Jul. 2018.

[135] X. Gao, F. Sossan, K. Christakou, M. Paolone, and M. Liserre, "Concurrent voltage control and dispatch of active distribution networks by means of smart transformer and storage," *IEEE Trans. Ind. Electron.*, vol. 65, no. 8, pp. 6657–6666, Aug. 2018.

[136] K. Worthmann, C. M. Kellett, P. Braun, L. Grüne, and S. R. Weller, "Distributed and decentralized control of residential energy systems incorporating battery storage," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1914–1923, Jul. 2015.

[137] Y. Song *et al.*, "Optimal operation of battery energy storage system considering distribution system uncertainty," *IEEE Trans. Sustain. Energy*, vol. 9, no. 3, pp. 1051–1060, Jul. 2018.

[138] P. Ariyaratna, K. M. Muttaqi, and D. Sutanto, "A novel control strategy to mitigate slow and fast fluctuations of the voltage profile at common coupling point of rooftop solar PV unit with an integrated hybrid energy storage system," *J. Energy Storage*, vol. 20, pp. 409–417, 2018.

[139] B. Olek and M. Wierzbowski, "Local energy balancing and ancillaryservices in low-voltage networks with distributed

[140] L. H. Macedo, J. F. Franco, and M. J. Rider, "Optimal operation of distribution networks considering energy storage devices," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2825–2836, Nov. 2015.

[141] A. Di Giorgio, F. Liberati, A. Lanna, A. Pietrabissa, and F. D. Priscoli, "Model predictive control of energy storage systems for power tracking and shaving in distribution grids," *IEEE Trans. Sustain. Energy*, vol. 8, no. 2, pp. 496–504, Apr. 2017.

[142] A. Saez-De-Ibarra, A. Milo, H. Gaztanaga, V. Debusschere, and S. Bacha, "Co-optimization of storage system sizing and control strategy for intelligent photovoltaic power plants market integration," *IEEE Trans. Sustain. Energy*, vol. 7, no. 4, pp. 1749–1761, Oct. 2016.

[143] "Alfen B.V," 2017, [Online]. Available: https://alfen.com/nl/nieuws/solar-global-kiest-voor-mega-energieopslags ysteem-van-alfen

[144] "US Department of Energy, Global energy storage database," 2019. [Online]. Available: http://www.energystorageexchange.org/

[145] "Navigant research leaderboard: Utility-scale energy storage systems integrators," 2020. [Online]. Available: https://www.navigantresearch.com/reports/

[146] "Fluence," 2018. [Online]. Available: https://fluenceenergy.com/wpcontent/ uploads/2019/02/lb-essi-18-executi ve-summary.pdf

[147] TenneT TSO BV, "End report FCR pilot," 2018, pp. 1–35. [Online]. Available: https://www.tennet.eu/electricity-market/ancillaryservices/ fcr-documents/ *Grid*, vol. 9, no. 3, pp. 2295–2303, May 2018.