Integration of a new thermal energy storage in electrical grids: power supply and control options

Matteo Scanzano
DIAEE – Electrical engineering
Sapienza University of Rome
Rome, Italy
matteo.scanzano@uniroma1.it

Maria Carmen Falvo
DIAEE – Electrical engineering
Sapienza University of Rome
Rome, Italy
mariacarmen.falvo@uniroma1.it

Fulvio Bassetti
Magaldi Power
Salerno, Italy
fulvio.bassetti@magaldi.com

Letizia Magaldi
Magaldi Power
Salerno, Italy
letizia.magaldi@magaldi.com

Antonio Scafuri
Magaldi Power
Salerno, Italy
antonio.scafuri@magaldi.com

***Abstract*—Climate change problems cannot be addressed without the decarbonization of energy production. For this reason, governments are promoting the use of Renewable Energy Sources (RES), especially wind and solar. In order to increase the penetration of RES, whose energy production cannot be controlled to follow the demand, more and more energy storage systems are needed, for ensuring adequacy and security to electrical power systems. This paper is focused on an innovative thermal energy storage technology based on fluidized solid particles, capable of receiving energy as electricity and storing it as heat for later use, e.g. produce steam for industrial applications. In such a system, electric energy is converted to heat by means of resistors, that can be supplied with AC and/or DC sources. In the paper, different use-case scenarios are presented, involving the grid and/or a photovoltaic plant as electric power sources. Then some possible power converters configurations are described and compared, to find the most appropriate solution for each scenario.**

Keywords—thermal energy storage, decarbonization, power systems, resistors, power converters, photovoltaics.

I. INTRODUCTION

In the last two decades, a lot of effort is being made all around the world to address climate change and global warming problems. As regards the energy sector, governments and international organizations have set various decarbonization targets for the future, promoting and funding the development of energy production from Renewable Energy Sources (RES), especially wind and solar. To achieve decarbonization targets for 2030, set by the European Union (EU), in 2020 the Italian Ministry for Economic Development published the National Integrated Energy and Climate Plan (PNIEC) [1], setting goals in various sectors: energy production, industry, transportation, residential, etc. For example, 55% of the electrical demand should be produced by RES in 2030. As stated in the National Recovery and Resiliency Plan (PNRR) [2], published by the Italian Government in May 2021, almost 6 billion euros will be employed to increase the share of Italian RES production, enforcing PNIEC targets.

However, unlike conventional power plants (e.g. thermoelectric), wind farms and photovoltaic (PV) parks are variable (“Variable Renewable Energy” - VRE), because they can produce a different amount of power based on weather conditions (wind velocity and solar irradiance), which can vary over time. The increase in VRE penetration into power systems raises several technical problems, such as reduced grid stability and system adequacy, with higher risks of blackouts [3][4].

Energy storage systems can be a solution to these problems, in fact they can provide various grid services, contributing to grid secure operation. A lot of research is being carried out all around the world and many energy storage technologies are being developed and tested, with different performances and costs [5][6]. Terna, the Italian Transmission System Operator (TSO), estimates that new 6 GW of energy storage systems (with respect to 2017) would be needed for the Italian power system in 2025, to ensure system adequacy, security and flexibility [7].

The present paper focuses on the electrical power supply and control options of a new thermal storage technology, integrated in power systems: STEM®-RES. Section II provides an overview of the proposed technology, along with a brief description of its particularities and some possible applications. In Section III, six use-case scenarios are presented, each one involving different amounts of electric energy exchanged between STEM®-RES, the grid and/or a PV plant. Section IV deals with the comparison of various ways to control the electrical power adsorbed by STEM®-RES systems, pointing out the major advantages and disadvantages of every solution. In Section V, two electrical system configurations are identified to connect STEM®-RES to the grid and PV, highlighting the importance of minimizing the use of AC/DC converters to reduce total costs. Then, the two configurations are compared, to find the optimal electrical power supply and connection solution for every scenario. Section VI contains the conclusions.

II. STEM®-RES TECHNOLOGY

The Italian company Magaldi Power has developed a new thermal storage technology: STEM® (Solar Thermo Electric Magaldi) [8]. Thermal energy is stored as sensible heat into a fluidized bed of solid particles, enclosed in an insulated metal container (a “module”). Modules are equipped with various components to allow energy exchange with external entities. Some components involve transformations between thermal energy (“Heat”) and electrical energy (“Power”) or vice-versa. Fig. 1 shows how the fluid bed becomes the core of a hybrid energy hub, with two inputs and two outputs, each provided by a specific set of components, described in the following.

Every module includes serpentine tubes immersed into the fluid bed, for heat transfer between solid particles and a fluid (i.e. steam). If serpentine tubes are supplied with steam at a higher temperature than that of solid particles, heat flows from steam to solid particles, charging the module. This enables STEM® technology to be used in "Heat-to-X" (H2X) applications. Dually, the module discharges if input steam temperature is lower than that of solid particles, since heat flows from solid particles to steam. This allows "X-to-Heat" (X2H) applications, where energy stored inside the module is used to produce steam for industrial process and heating.

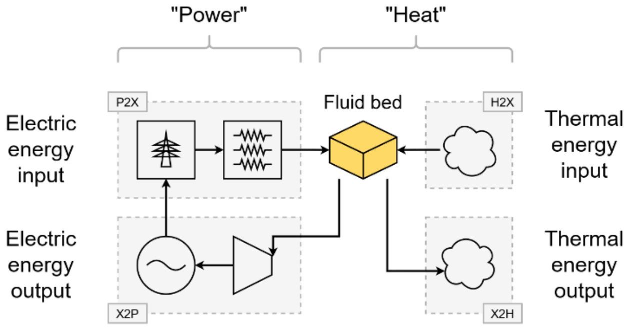

Fig. 1. Components of a STEM® system (thermal and electric energy hub)

With the addition of electrical heaters, modules can be charged with electric energy, directly converted to heat, stored into solid particles for later use. Such a system is called STEM®-RES (Renewable Energy Storage) [9], because it can be used in several applications involving VRE, providing various grid services to power systems. For example, STEM®-RES systems can be used to reduce overgeneration, charging modules in hours of high VRE production (and low energy prices), or to provide Demand Side Response (DSR) services acting as a controllable load. If needed, thermal energy can be converted back to electrical energy through a power block: steam can expand into a turbine, connected to a synchronous generator. For the majority of applications, only one energy input and one energy output are used. In such applications, four different options of input/output (I/O) energy types are possible, as summarized in TABLE I.

TABLE I. STEM® I/O OPTIONS

Energy input (charging)	**Energy output (discharging)**	
	Thermal output (X2H)	Electric output (X2P) (using power-block)
Thermal input (H2X)	H2H	H2P
Electric input (P2X) (using resistors)	P2H	P2P

When the module is being charged or discharged, the bed is kept in a fluidized state allowing immersed steam tubes to freely expand. Moreover, bed fluidization ensures a much higher thermal diffusivity and an improved heat exchange between solid particles and immersed elements (e.g. steam tubes). A typical module contains 500 tons of solid particles and can store different amounts of thermal energy (20-80 MWh), based on fluid bed temperature (up to 620 °C, for superheated steam generation). Multiple modules can be used together for an increased thermal storage capacity and input/output power, connecting steam tubes from different modules in series, parallel, or both, according to the needs of each application. When energy exchange is not needed, the auxiliary systems for bed fluidization can be turned off, providing cost-effective long-time storage, with minimal energy loss for heat conduction through the thermal-insulated walls of the module. It must be noted that the fluidization system can be used to control the heat exchange between solid particles and serpentine tubes.

Major advantages of STEM®-RES technology are modularity, flexibility and low environmental impact, since its construction does not require pollutant, poisonous, flammable or other dangerous materials, thus considerably simplifying and shortening authorization processes. In addition, land use per stored energy unit is limited. These features may allow STEM®-RES technology to become an attractive alternative to pumped-hydro storage systems, however power blocks (for energy conversion from heat to electrical energy) have limited efficiency and this may act as an obstacle for thermal energy storage technologies deployment in "Power-to-Power" (P2P) applications. For this reason, the majority of current STEM®-RES research efforts are focused on "Heat-to-Heat" (H2H) and particularly on "Power-to-Heat" (P2H) applications, schematized in Fig. 2.

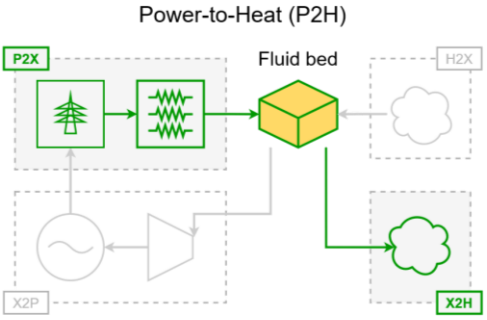

Fig. 2. Components of a STEM®-RES P2H system.

III. USE-CASE SCENARIOS

In STEM®-RES P2H applications, where electrical energy is converted to heat (transferred and stored into solid particles), the relevant electrical loads are the electrical heaters. In the first instance, the power demand of the auxiliary systems (e.g. compressors and fans for solid particles fluidization, etc.) can be neglected.

STEM®-RES heaters can be connected to different electric power sources (the grid, a RES plant, or both). In this paper, six STEM®-RES use-case scenarios (each labelled by a letter, A-F) are identified and examined. In two scenarios all the electric power is supplied to STEM®-RES by only one source: the grid (A) or a PV plant (D). In the other four scenarios, both sources are used together, providing different shares of energy. In E and F scenarios, power exchange with the grid is reversed, so energy is fed to the grid.

The six scenarios, summarized in TABLE II. , are listed in the following:

A. all power is provided by the grid, there is no PV plant;

B. the majority of power for the heaters is provided by the grid, a small amount by PV;

C. the majority of power for the heaters is provided by the PV plant, and a small amount by the grid;

D. all power is provided by PV, there is no connection to the grid;

E. PV supplies the heaters and a small amount of power is fed to the grid;

F. PV generates a lot of power, all fed to the grid except for a small amount, for STEM®-RES heaters.

In general, regarding the power provided by the grid (P_{GRID}), and by the PV (P_{PV}) and that adsorbed by STEM®-RES resistors (P_R), energy conservation must be met:

$$P_R = P_{GRID} + P_{PV} \tag{1}$$

where P_R and P_{PV} are always positive (or zero), and P_{GRID} is positive when power is drawn from the grid (negative if fed). Power losses in transformers, converters, cables, and other elements are neglected.

In practical cases, the power provided by the PV plant varies with weather conditions, therefore P_{PV}, P_{GRID} and P_R are not constant over time. In order to consider different operating conditions (e.g. full-power or partial loads) for the same system, multiple scenarios should be taken into account at the same time. In the present paper, for simplicity, only the nominal operating conditions are considered, so each scenario is independent of the others.

TABLE II. USE-CASE SCENARIOS

Scenario		Power from		Power to	
		Grid	***PV***	***Grid***	***Heaters***
A	$P_{PV} = 0 \rightarrow P_R = P_{GRID}$	xxx			xxx
B	$P_R > P_{GRID} > P_{PV} > 0$	xx	x		xxx
C	$P_R > P_{PV} > P_{GRID} > 0$	x	xx		xxx
D	$P_{GRID} = 0 \rightarrow P_R = P_{PV}$		xxx		xxx
E	$P_{PV} > P_R > \lvert P_{GRID}\rvert$, $P_{GRID} < 0$		xxx	x	xx
F	$P_{PV} > \lvert P_{GRID}\rvert > P_R$, $P_{GRID} < 0$		xxx	xx	x

Note: more “x” indicates more power.

Fig. 3 illustrates a simple and useful chart for comparison among scenarios. It has P_{PV} on the y-axis and P_{GRID} on the x-axis, therefore every operating point of the system (every combination of different values for power exchange between the grid, PV and STEM®-RES heaters) is represented by a unique point of the chart. Since PV can only generate power ($P_{PV} \geq 0$), negative values for the y-axis are not allowed. In addition, since resistors can only adsorb electrical energy ($P_R \geq 0$), power fed to grid cannot excess power from PV ($P_{PV} \geq -P_{GRID}$), so the bottom half of the top-right quadrant (filled with grey in Fig. 3) cannot be considered. Every scenario corresponds to a specific region of the chart, delimited by dashed lines and axes. For points along the y-axis (D scenario) no power is exchanged with the grid. In scenarios to the left of the y axis (A, B, C), power is absorbed by the grid and the whole system act as a load. For scenarios on the other side of the y-axis (E, F) power is fed to the grid, and the system act as a generator.

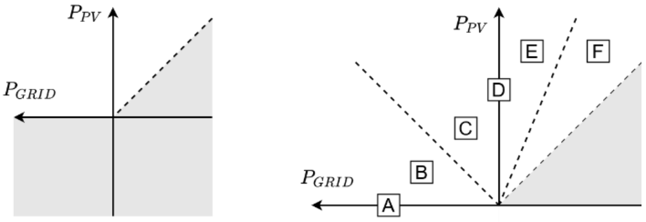

Fig. 3. Chart for STEM®-RES P2H case-use scenarios comparison

IV. ELECTRICAL POWER CONTROL SOLUTIONS

Electrical heaters must act as a controllable load, so a power control mechanism is needed. Since they are resistive elements, they can be supplied with AC or DC, so both solutions are examined, then compared.

For STEM®-RES prototypes at Magaldi factory in Buccino (Italy), thyristor-based AC regulators have been employed to control resistors power (up to 500 kW), using Zero Voltage Switching (ZVS) technique. However, the harmonic and sub-harmonic content of the drawn current may result in increased losses in power transformers [10], induction motors [11] and cables. Moreover, harmonics may disturb other electric equipment (e.g. digital control and supervisory systems) or cause protection systems malfunctions [12]. For systems above 500 kW, these problems could have a relevant impact, therefore in the following, some alternative solutions are presented.

A simple and cost-effective solution for AC resistors power control is star-delta reconfiguration. Individual resistors can be connected inside the module as illustrated in Fig. 4, so every resistor bank can be controlled to adsorb 100%, 33% or 25% of full-power using contactors.

Fig. 5 shows the three possible connections between resistors that can be obtained through the proposed variant of the star-delta reconfiguration technique. This solution is particularly interesting because commercial star-delta motor starters can be used [13].

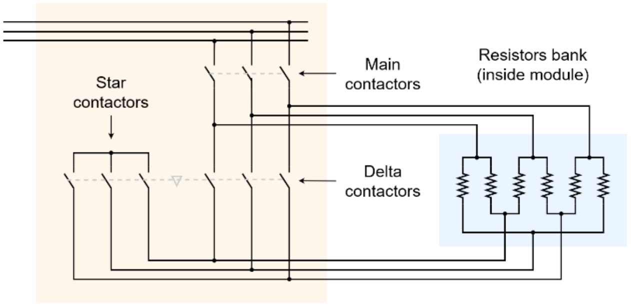

Fig. 4. Connection scheme of a STEM®-RES resistor bank to its star-delta power control system. Protection systems are not shown.

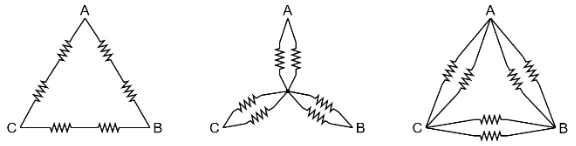

Fig. 5. Possible connections of individual resistors of a STEM®-RES resistors bank. From left: 25%, 33%, 100% of full-power.

Another power control technique for AC involves transformers with On Load Tap Changer (OLTC) to control voltage applied to resistors. Since OLTCs are commonly used for fine voltage control in power grids (typically between ±1% and 10%), commercial transformers with OLTC are not able to control resistors power on a wide range. However, custom transformers or autotransformers with dedicated taps (one for each desired power setting), can be used. An interesting solution is to use two different techniques together, for example, star-delta reconfiguration for coarse power control and commercial transformers with OLTC for fine power control.

For DC resistors, several series-parallel reconfiguration techniques can be considered, but they involve a lot of switches, especially if more than two power settings are required. An alternative solution is to use DC/DC converters, that can provide power control over a wide range. Fig. 6 illustrates a simplified schematic of a DC/DC resistors power control system based on buck converters [14]. It should be remarked that power electronic converters are usually quite expensive and their life is considerably shorter than mechanical switching systems. On the other hand, power converters allow accurate and continuous control of the exchanged power, that cannot be obtained using star-delta or series-parallel reconfiguration techniques.

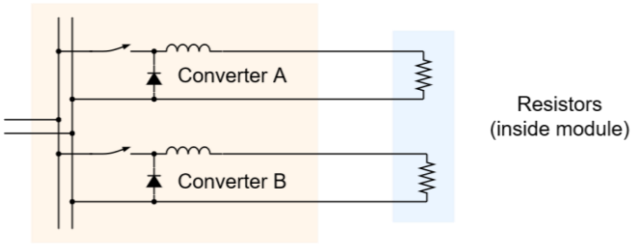

Fig. 6. Example of DC/DC buck converters for DC resistors power control.

V. ELECTRICAL POWER SUPPLY SOLUTIONS

In this section, two electrical system configurations are identified to connect STEM®-RES heaters to the grid and PV:

- configuration 1: AC heaters;
- configuration 2: DC heaters.

The proposed configurations 1 and 2 are illustrated in Fig. 7 and Fig. 8, respectively. AC elements are colored in red and DC elements in blue. Then, all the combinations of energy flow scenarios and system configurations (A1, A2, B1, B2, C1, C2, …) are analyzed, to find the optimal electrical connection solution for every scenario.

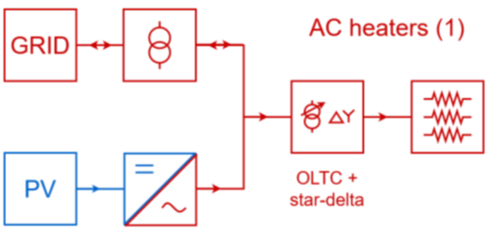

Fig. 7. Configuration 1, for the electrical power supply and connection between the AC grid, a PV plant (DC) and STEM®-RES AC heaters.

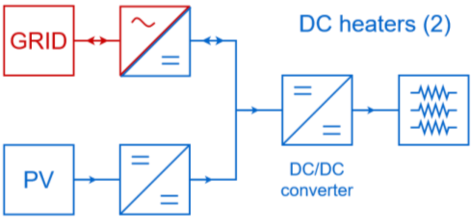

Fig. 8. Configuration 2, for the electrical power supply and connection between the AC grid, a PV plant (DC) and STEM®-RES DC heaters.

Both configurations involve an AC/DC converter (to connect AC and DC elements together), which allow fine power control with limited harmonic impact on AC elements.

As clear from Fig. 7, for configuration 1 (AC connected heaters) the AC/DC converter must be sized on PV peak output power. For configuration 2 (DC connected heaters) the AC/DC converter must be sized on maximum power exchange with the grid (Fig. 8).

$$P^{(1)}_{AC/DC} = P_{PV} \qquad P^{(2)}_{AC/DC} = |P_{GRID}| \tag{2}$$

AC/DC converters may be 12-pulse thyristor bridges or IGBT inverters. If connected to a fixed-voltage DC bus, thyristor bridges can only convert power in one direction, therefore a bidirectional power exchange between AC and DC is not possible. On the contrary, IGBT inverters can exchange power in both directions, with reduced harmonics.

AC/DC conversion systems are the most expensive elements among those included in the identified configurations, therefore total system costs depend heavily on converters rated power. In order to facilitate the widespread of STEM®-RES technology, system design choices should be made to achieve the best trade-off between technical performance and cost.

STEM®-RES modules are designed to have a long technical life, potentially over 40 years with appropriate replacement of some auxiliary components. Since power electronic converters have a shorter technical life, their use in the electrical connection system can lead to significant costs for their substitution. Consequently, the use of large AC/DC converters should be avoided, unless absolutely necessary. In this view, the optimal system configuration is the one that allows minimizing AC/DC converters rated power, so configuration “1” (AC resistors) is preferable to the other if the following conditions are met:

$$P^{(1)}_{AC/DC} < P^{(2)}_{AC/DC} \rightarrow P_{PV} < |P_{GRID}| \tag{3}$$

In reference to each case-use scenario, it is possible to find the most competitive solution, considering that:

- A1 is the simplest and convenient solution because, since there is no PV plant, no power electronic converters are involved and the whole power flows from the grid to resistors. Conversely, A2 needs a full-power AC/DC rectifier, so it is one of the most expensive solutions.
- B1 solution, quite convenient, requires a small DC/AC inverter for the small PV plant. For B2 solution, an almost full-power AC/DC rectifier is needed, resulting in a high cost, similarly to A2.

- C1 solution involves an almost full-power DC/AC inverter. Such a system is quite expensive, certainly more than C2 solution, where only a small AC/DC rectifier is needed.
- D1 solution requires a high-cost full-power DC/AC inverter. Only a DC/DC conversion system is needed for D2 solution, definitely more convenient.
- Similarly to D1, also E1 solution involves an expensive DC/AC inverter. Only a small and quite cheap DC/AC inverter for grid connection is required in E2 solution.
- Both F1 and F2 solutions need a high-cost DC/AC inverter to convert the large amount of power produced by the PV plant. F2 requires a slightly smaller inverter than F1, but F2 involves also a small DC/DC converter. Consequently, there is no significant cost difference between the two.

The optimal solutions for each case-use scenario are summarized in TABLE III. and Fig. 9:

TABLE III. OPTIMAL SOLUTIONS FOR EACH SCENARIO

Scenario	**A**	**B**	**C**	**D**	**E**	**F**
AC resistors (1)	x	x				x
DC resistors (2)			x	x	x	x

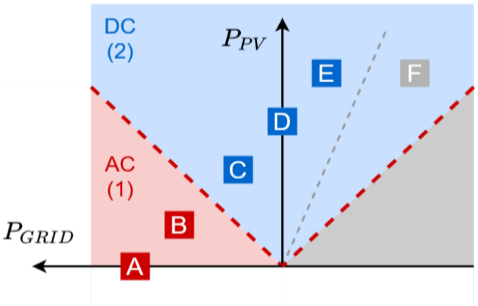

Fig. 9. Optimal solutions (AC resistors: red, DC resistors: blue) for every zone of the case-use scenarios comparison chart.

VI. CONCLUSIONS

STEM® technology is a modular, cost-effective and environmentally friendly solution for thermal energy storage based on a fluidized bed of solid particles, that can act as the core of hybrid electrical/thermal energy hubs.

In the actual and future market contexts, Power-to-Heat (P2H) applications have a high potential for the decarbonization of the energy sector. In such applications, resistors are used to convert electrical input energy into heat, stored into the fluidized bed, with minimal losses.

Thermal energy can be used to produce steam or other heat transfer fluids for various industrial processes. Resistors can be connected to a lot of different sources: six use-case scenarios (involving connection to the grid, a PV plant, or both) have been identified.

Since resistors can be supplied with AC or DC, various power control solutions have been described, highlighting advantages and disadvantages. Then, two electrical connection system configurations have been presented, each involving different components.

For every scenario A-F the most convenient solutions have been identified, through techno-economic considerations, including AC/DC power converters cost.

REFERENCES

[1] Italian Ministry for Economic Development (MiSE), “National Integrated Energy and Climate Plan”, 2020. https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf

[2] Italian Government, “National Recovery and Resiliency Plan”, May 2021. https://www.governo.it/sites/governo.it/files/PNRR_0.pdf

[3] IRENA, “Electricity storage and renewables: Costs and markets to 2030”, October 2017, ISBN 978-92-9260-038-9.

[4] IRENA. “Power system flexibility for the energy transition”, November 2018, ISBN 978-92-9260-089-1.

[5] K. Mongird, V. Fotedar, V. Viswanathan, V. Koritarov, P. Balducci, B. Hadjerioua, J. Alam, “Energy Storage Technology and Cost Characterization Report”, July 2019.

[6] X. Luo, J. Wang, M. Dooner, J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation", Applied Energy, vol. 137, 2015, pp. 511-536, ISSN 0306-2619.

[7] Terna, National Transmission Network Development Plan 2020. https://download.terna.it/terna/Piano%20di%20Sviluppo%202020_8d7db1ffa4ca9e7.pdf.

[8] Magaldi, STEM Concentrated Solar Power, 2018. https://www.magaldi.com/en/products-solutions/csp-concentrating-solar-power

[9] Magaldi, STEM-RES Energy Storage System, 2018. https://www.magaldi.com/en/products-solutions/renewable-energy-storage-system-res

[10] D. Pejovski, K. Najdenkoski, M. Digalovski, "Impact of different harmonic loads on distribution transformers", Procedia Engineering, vol. 202, 2017, pp. 76-87, ISSN 1877-7058.

[11] J. P. G. De Abreu and A. E. Emanuel, "The need to limit subharmonics injection," *Ninth International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.00EX441)*, 2000, pp. 251-253 vol.1, DOI: 10.1109/ICHQP.2000.897033.

[12] C. Roldán-Porta, G. Escrivá-Escrivá, F. Cárcel-Carrasco, C. Roldán-Blay, "Nuisance tripping of residual current circuit breakers: A practical case", Electric Power Systems Research, vol. 106, 2014, pp. 180-187, ISSN 0378-7796.

[13] A. Hughes, B. Drury, "Induction Motors – Operation from 50/60Hz Supply", ch. 6, Electric Motors and Drives (Fourth Edition), Newnes, 2013, pp. 169-204, ISBN 9780080983325.

[14] Mohan, Ned, Tore M. Undeland, and William P. Robbins. “Power electronics: converters, applications, and design”. John Wiley & sons, 2003.