OPERATIONS DECARBONIZATION IN DOWNSTREAM FACILITIES WITH PROCESS ELECTRIFICATION

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Abstract - The pivotal role of process electrification in the decarbonization of downstream oil, gas, and petrochemical facilities is underscored in this paper. Electrification technology supplants major fossil fuel consumers with electricity-driven processes, with process heating and process motion representing key end uses with substantial electrification potential. This transformation encompasses not only electrically driven compressors and process heaters but also necessitates a significant expansion—by a factor of 10 to 20—of a plant's power system.

The optimization of demand, entailing the modification of consumption patterns in continuous processes, presents an intriguing challenge. Critical factors contributing to the feasibility of process electrification in heavy process industries encompass optimized power system design, clean power procurement, and demand-side flexibility. A notable early success involved the convergence of two key technologies: electric and digital. This paper delves into a systematic approach to process electrification, considering various implications, including access to green electricity, the planning and design of optimal electrical infrastructure, and the safety and efficiency of electrified processes. As process electrification increasingly shifts process loads to electricity consumers, the imperative to manage the intricate relationship between power and process systems in these electrified plants becomes more pronounced. The latter part of this paper explores the utilization of digital simulation at the system level to model the future state of the system and to identify bottlenecks in the transition from the current energy mix of the facilities.

I. INTRODUCTION

Amid the substantial emphasis on novel, low-carbon energy systems, prevailing fossil fuel-based energy systems persist within the energy mix across virtually all modeling scenarios for the foreseeable future. Likewise, with the ongoing evolution of the global economy and the burgeoning of global wealth, the demand for bulk chemicals is poised for significant growth. Consequently, the decarbonization of operations within upstream and downstream oil, gas, and chemicals facilities stands as an essential component of the energy transition.

Direct industrial emissions presently contribute to 26% of global emissions, with industrial energy consumption witnessing an average annual increase of 1%. Consequently, the decarbonization of operations constitutes a paramount concern for both producers and regulators, prompting the exploration of various decarbonization pathways. Although modest enhancements in industrial productivity and energy efficiency, coupled with policy adjustments, have yielded favorable outcomes, the rate of progress remains notably sluggish. There is an urgent need for a rapid pathway to achieve net zero emissions within industrial processes on a global scale.

Industrial emissions largely stem from the utilization of fuels, with fossil fuels representing 78% of the industrial energy mix, while electricity constitutes a mere 22%. Despite concentrated efforts to decarbonize electricity generation, there exists a compelling case for reevaluating the energy mix in downstream plants and adjusting the demand side. Given that electricity stands as the most efficient form of energy and a premier decarbonization tool, process electrification emerges as a prime decarbonization pathway for chemical and heavy industries.

Process electrification denotes the shift from fossil fuel-powered processes—such as compression, steam generation, and process heating—to electrically driven processes. This transition is optimally paired with digital technology to ensure judicious, effective, and timely utilization of electricity in processes. Consequently, process electrification signifies a fundamental change for all stakeholders, influencing the design, construction, and operation of plants, as well as impacting the supply chain, commercial contracts, and plant profitability, alongside the human dimension of the transformation. Anticipated outcomes of process electrification include the emergence of clusters or islands of substantial electricity consumers, thereby engendering repercussions that extend beyond the plant's boundaries, entailing interactions with power grids, distributed power generation, and other electricity consumers.

Process electrification represents the forthcoming industrial evolution, a large-scale shift imperative for a net-zero world. In the initial stages of this transformation, the energy mix is anticipated to evolve gradually, signifying that most plants and processes will function in hybrid configurations. These configurations will intelligently integrate fossil fuels, electricity, and emerging energies such as green hydrogen to maintain emissions at target levels, while minimizing impacts on production and upholding power grid stability. Process electrification demands innovation across various domains –

encompassing process technology, control and optimization, artificial intelligence for forecasting and process flexibility management, advanced power systems and power control technologies, new power sources, and energy storage systems, among others. This transition necessitates collaboration and coordination among process licensors, industrial technology firms, regulators, power companies, and end users.

Early examples of process electrification in upstream offshore and FPSOs are good indicators of the high value of electrification technologies. Similarly, electrification of upstream onshore operations by major operators in the United States proves not only the decarbonization potential of electrification, but also the improvements in efficiency. At the same time, the challenges faced by many operators to scale up electrification is an indication of the need for a systemic approach to process electrification.

II. PROCESS ELECTRIFICATION IN DOWNSTREAM FACILITIES

A. Electrification of Motion and Process Heating

Process electrification is divided into two primary domains. The initial classification pertains to the electrification of motion, encompassing the transition from fossil fuel-based mechanical propulsion systems, such as gas turbine-driven compressors, to electrically powered compressors utilizing motors and variable frequency drives (VFD). This domain also encompasses the electrification of large pumps and diesel engine-driven rotating machinery. The electrification technology in this domain has reached a mature stage and is widely embraced within the industry.

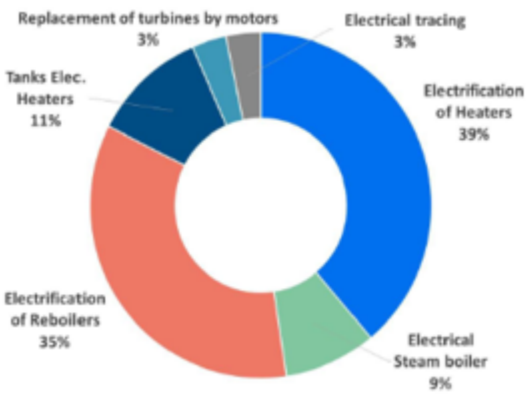

Fig 1: Refinery Process Electrification Scope[1]

The second category involves the electrification of process heat, encompassing activities such as steam generation through electric boilers, electrification of re-boilers, and the conversion of fired heaters to e-Heaters. While electrifying small and medium heating duties is feasible with existing technology, the electrification of large process heaters with high heat flux, like cracking furnaces, is rapidly progressing to align with the corresponding fired duty at the installed base. However, the challenge of scaling up is not primarily associated with the electric heating technology itself, but rather with other factors such as the electrical system capacity of the facility, available electrical infrastructure, complexities in green power procurement, and various engineering hurdles. A typical breakdown of a refinery electrification scope is represented in Fig1.

Majority of the refinery energy consumption is attributable to heat energy required by various refinery processes. Boilers and reboilers account for 44% of the energy demand, while furnaces and heaters account for 39%. Other static heaters for Tank heating and heat tracing account for another 14%. Replacement of turbines by electric motors only account for around 3% of the total electrification scope. In many refineries, electric heat tracing has progressively replaced conventional steam tracing. Small electric heaters are already in use for processes such as gas or lube oil skid heating. Hence the focus of a downstream refinery electrification is mainly on the larger heaters, steam boilers and reboilers.

B. Challenges to Electrification

The primary obstacle in electrifying downstream refineries or petrochemical plants is related to power systems. Presently, the electrical energy accounts for less than 10% of the total energy consumption in refineries. Expanding the electrification to the refinery processes outlined in figure 1 would necessitate a 10 to 20-fold growth in the refinery's electrical systems. Even a 10% electrification of the facility would significantly impact both the energy supply and the electrical distribution systems within the facility. Such substantial capacity expansion in electrical systems mandates close coordination with power grid and utility companies. Given the age and layout of the major refining and petrochemical facilities, electrical systems present a significant bottleneck in process electrification projects. An essential strategy to embrace in the initial stages of project planning is to formulate a scalable and adaptable electrical distribution architecture for the facility.

Process electrification necessitates a distinct approach to process safety, as it blurs the distinction between functional and electrical safety, emphasizing the latter as a crucial element of the former. Operating and maintaining electrified process units demands specialized training and a shift in mindset. Consequently, preparing the workforce for process electrification stands as a pivotal aspect of this transition.

The electrification of process heaters diminishes the need for fuel gas in a refinery and reduces reliance on imported natural gas, stemming from demand fluctuations within the facility. However, this shift could lead to surplus fuel gas production if not utilized by other process units like boilers or downstream petrochemical units. Modern petrochemical complexes, such as ethylene plants, employ cutting-edge heat recovery and integration techniques. For instance, recovering heat from a cracking furnaces aid in steam generation for use in the steam cracker. Electrification has the potential to disrupt the existing energy /steam balance within a facility, a critical consideration given the gradual nature of downstream electrification. It's imperative to ensure energy and steam balance across the entire facility during this transition. Consequently, a key challenge lies in obtaining a comprehensive overview of the plant's energy systems and their interdependencies to develop a feasible electrification roadmap.

C. Value beyond decarbonization.

The primary impetus for downstream electrification is decarbonization, yet this transformation yields supplementary advantages for operators. Electrified process units generally exhibit heightened energy efficiency, thereby reducing long-term operational expenses. Furthermore, electrification significantly enhances process controllability, driving up efficiency and lowering maintenance costs in comparison to traditional turbines and fired heaters. Properly designed and implemented electrification also leads to elevated levels of operational safety. An implicit benefit of electrification is its facilitation of remote operations. Collectively, process electrification culminates in a reduced levelized cost of ownership despite the higher initial capital expenditure. Moreover, the ability to partake in grid flexibility schemes presents an additional revenue stream for operators, where available.

III. SYSTEMS APPROACH TO PROCESS ELECTRIFICATION

The electrification of downstream refining and chemical facilities necessitates a comprehensive approach that encompasses all aspects from design to operations. Primarily, it must seamlessly integrate into the decarbonization strategy and be reinforced by factors like long-term power purchase agreements (PPA), risk management strategies, and more. As a result of electrification, the facility will emerge as a significant consumer on the grid, thereby underscoring the importance of grid resiliency as an external consideration. Internally, the implementation of a robust energy management system (EMS) assumes critical importance. The expected performance and functionalities from the EMS significantly differ from most existing systems, highlighting the need for a novel approach to meet these requirements.

The process electrification customer journey involves three interconnected activities, necessitating a systems design approach. The first activity pertains to the design of electrified processes, which will involve collaboration with the process licensor or an engineering specialist for license-free processes. The second activity focuses on electrical system design, entailing the redesign of the electrical architecture to accommodate the anticipated shift towards electrical energy dominance in the future energy mix. The third element involves devising control and automation strategies for the electrified processes and integrating them into existing systems and processes. Of utmost significance is the heightened interdependence between the power system and the process system within the facility. This elevated level of interdependency renders it impractical to design, operate, and optimize these systems in isolation.

TABLE I

ETHYLENE PLANT MODEL - CO_2 PRICE VS ENERGY PRICE

CO_2 Price	Greenfield Plant		
Country	USA	EU	China
40 €/tCO_2	40	51	50
80 €/tCO_2	54	65	64
120 €/tCO_2	69	78	77
160 €/tCO_2	83	92	91

The electrification of processes in a downstream facility demands a strategic approach. The initial phase involves modeling, analyzing, and comprehending the potential for electrification. This encompasses a thorough techno-economic analysis to ascertain the suitability of electrification for the chosen assets in comparison to alternative scenarios. The comprehensive model integrates process energy demands, direct and indirect capital expenditures, energy costs at the intended site, power, PPAs, grid carbon intensity, and carbon taxes/incentives into the evaluation. Table 1 below represents the example of an ethylene plant. The table is the model[1] output showing the required carbon and energy prices for full plant electrification to be viable. In this example, at a carbon price of 120€/ t CO_2, the PPA price necessary to make full plant electrification viable is 69-78€/MWh for a greenfield plant depending on the country. Fig 2 shows the modelling approach employed in this exercise.

Upon successful validation of the business case, the subsequent step involves assessing technical feasibility and developing detailed designs for electrified processes and the associated electrical infrastructure to facilitate the transition. Simultaneously, engagement with utilities is essential to assess grid resiliency and prepare for

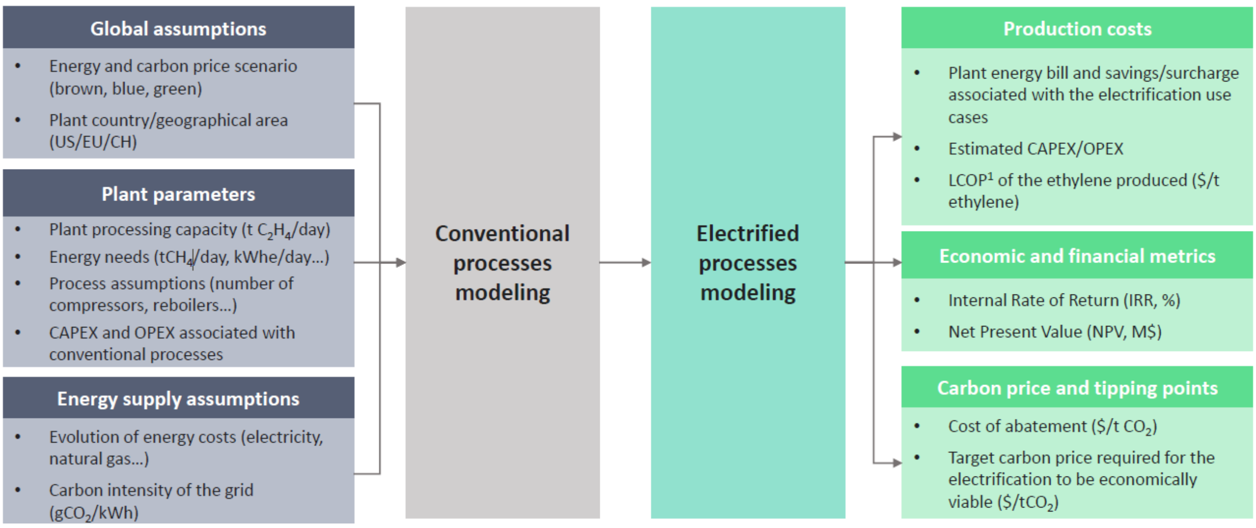

Fig 2: Ethylene Plant economic model configuration

interconnection. Prior to a capital expenditure decision, operators must secure PPAs or deploy onsite microgrids or distributed energy resources (DER) mechanisms. The culmination of these activities produces an electrification roadmap outlining the sequence of assets earmarked for electrification. The selection of an electrification project represents a significant decision. Each facility presents numerous readily achievable opportunities that offer substantial return on investment (ROI) in terms of carbon footprint reduction. Initial projects may involve the implementation of VFDs, substitution of steam tracing with electric heat tracing, conversion of pneumatic systems to electric, and the transformation of reboilers and small heaters to electric, among others. Criteria for selecting starter projects include technology maturity and minimal impact on the facility's energy or steam balance. Electrifying larger heaters, furnaces, and compressors constitutes major projects that necessitate a comprehensive reevaluation of the electrical, control, and automation aspects along with a comprehensive energy management system.

A. Electrified Process Design.

An all-electric process design entails the utilization of electrical energy as the primary energy source for process units. Emerging methodologies in hydrocarbon processing and chemical manufacturing, such as electrochemical processes, photochemical reactors, and rotodynamic crackers, are currently undergoing development across various stages. However, these technologies are not anticipated to reach commercial scale within the next decade. Consequently, existing facilities continue to represent a significant portion of industrial energy demand. Given the current level of technical maturity, an electric process design relies on electric heating elements to supply the requisite heat energy for process units, as well as electric drivers for process fluid movement and compression. While these technologies have been in existence for many decades, design choices wield substantial influence over the overall efficacy of electrification. Notably, electric process heating demands particular attention.

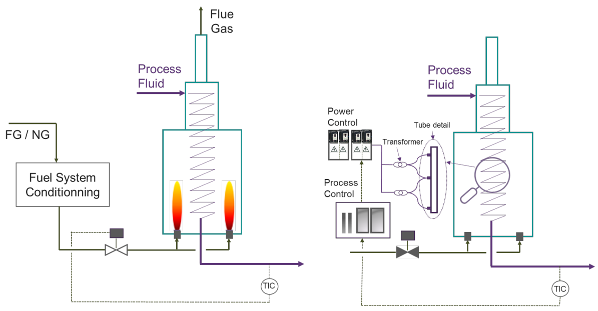

Fig 3: Fired heater vs a e-Heater with direct heating technology.

The prevalent approach involves radiative heating design utilizing electric heating elements, a method highly proficient in converting electrical energy into heat energy. Nonetheless, depending on the heater or furnace design, the heat transfer efficiency may hover at 35% or lower, thereby diminishing the overall efficiency of the electric furnace. Alternatively, the adoption of direct heating technology for tubular heaters markedly enhances heat transfer efficiency, given the direct transfer of heat to the process fluid.

When designing electrified process units, the nominal operating voltage is a critical factor. Industrial heaters and furnaces can be tailored for either low voltage (LV) or medium voltage (MV) applications. The choice between the two depends on various factors, as there is no one-size-fits-all solution suitable for all types of process heaters. MV heaters are favored for their ability to lower cabling and copper costs as well as power losses. Among industrial electric heater manufacturers, the 4.16kV or 6kV design is popular, particularly for enclosed tubular designs or e-boilers. However, MV heater designs may not be feasible for many downstream process units due to concerns about electrical safety and lower temperature control accuracy. Process units such as cracking furnaces, which require accessibility for inspection and maintenance by plant personnel, as well as precise power and temperature regulation, present greater challenges for MV designs.

In contrast, LV heaters offer simpler interconnections and greater potential for precise temperature control. They are preferred for safety considerations. It is feasible to design high-temperature and high-heat-density LV heaters with a safety voltage (<50V) for applications that involve frequent access and human interactions. However, LV heaters require higher currents to achieve the necessary power density. Therefore, it is crucial to design the overall LV distribution system to minimize heat losses. The use of heating elements with higher resistivity can significantly reduce the electric current required to achieve the power density, thereby reducing the maximum current rating specifications for the LV switchgear.

B. Electrical Distribution System architecture

The process of devising electrical system architecture comprises two primary elements: the design of the electrical distribution system and the design of the power control circuits (Feeder circuits) at the load side. The electrical distribution architecture must fulfill two major objectives. The foremost objective is the capacity to scale up the system to accommodate capacities of 1 GW or more. At this scale, the electrical infrastructure constitutes a substantial portion of the overall cost of process electrification. Therefore, the second objective of the electrical architecture is to optimize the MV and LV equipment as well as cables. Optimal selection of voltage levels is crucial for cost-effective designs.

The choice of High Voltage (HV) depends on local utilities and the total power demand on the site. Systems exceeding 500MVA are typically interconnected at or above 145kV. While there is less flexibility in selecting HV voltage levels, MV voltage levels can be tailored to suit the process requirements while reducing overall equipment and cable costs. It is common practice for electrical system designers to select MV voltages from those used by local utilities. However, utility voltages are seldom optimal for industrial power systems. Adopting 2 or 3 voltage levels for the MV system is considered a best practice. One voltage level is allocated for site distribution, while one or two voltage levels cater to the process supply, considering the power demand and voltage drops for motor feeders. Similarly, one or two levels of the LV system (400/690V or 480/600V) are chosen to align with busbar ratings and short-time withstand capabilities within the specified parameters. Consequently, HV/MV transformer specifications (short-circuit impedance, MV voltage) significantly impact the cost and performance of the power system. Figure 4 illustrates a reference architecture for a 1 GW petrochemical facility, adhering to the aforementioned guidelines.

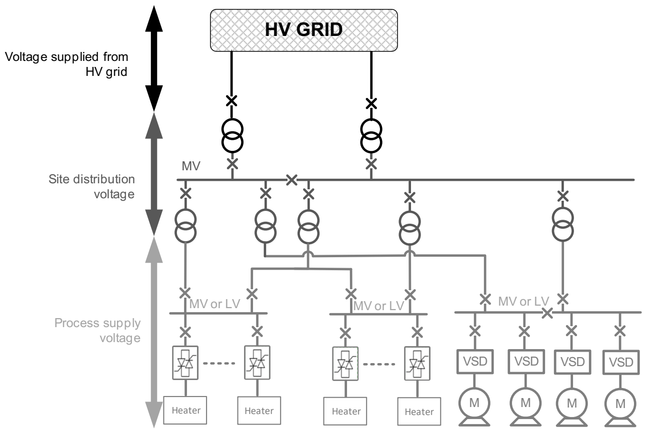

Fig 4: Reference Architecture of a 1 GW electrical system

C. Power Control System Design for Electric Heaters

When considering the power supply and control system for electric heaters on the load side, there exist several approaches to design. The selection of a power supply system hinges on the desired level of performance, specifically focusing on control modularity, control dynamics, and total harmonic distortion. A straightforward approach involves the use of MV/LV on-load tap changer transformers for voltage regulation. This design is well-suited for applications where modular control is not required, and the control dynamics are within the unit of minutes. A primary advantage of this system is its generation of no harmonics, thereby obviating the need for harmonic mitigation techniques. This configuration is illustrated in figure 5.

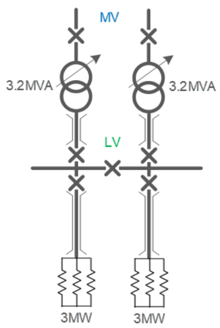

Fig 5: A 6 MW heater power supply with OLTC transformer

Alternatively, the control modularity of the system can by enhanced by employing a modified arrangement as depicted in figure 6, to reduce power losses in cable by bringing MV closer to the heater circuits.

In scenarios where the control dynamics demand is more rigorous, the implementation of a power supply system integrating thyristor (MV or LV) becomes necessary. The power control circuit featuring thyristors can effectively fulfill control dynamics in the range of milliseconds. However, it is important to note that if heaters require a phase control firing of the thyristors this system introduces notable harmonic distortion (8 – 15%). Consequently, the incorporation of passive filters into the architecture is imperative for harmonic mitigation. An example of such configuration is illustrated in figure 7.

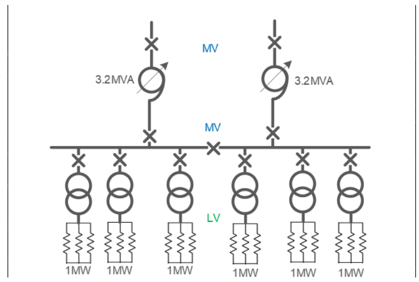

Fig 6: Alternative design for 6 MW heater power supply with higher control modularity

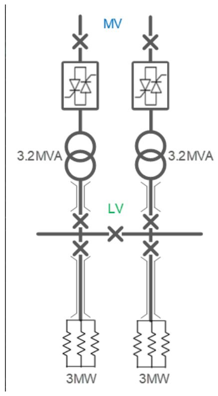

Fig 7: a 6MW heater power supply design with MV Thyristor control for temperature regulation

A power supply design employing low-voltage thyristors and eventually low-voltage transformers (depending on heaters type) allows for modular control, with the added capability of achieving control dynamics at the millisecond level. This configuration introduces a maximum of 8% harmonic distortion to the system in case of phase angle firing. Nevertheless, the integration of low-voltage active filters into the circuit enables the reduction of harmonic distortion to below 3%. This configuration is illustrated in figure 8.

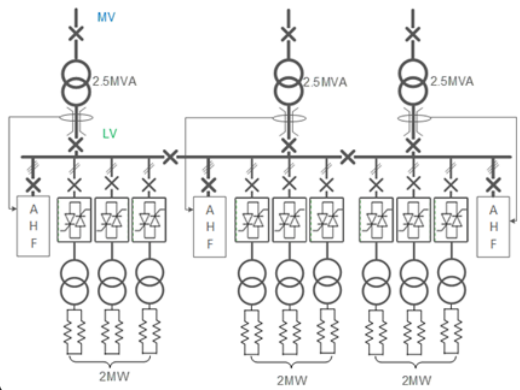

Fig 8: a 6MW LV heater power supply design with LV Thyristor control and LV transformers for temperature

A hybrid control variant of the solution involves the amalgamation of heater control through thyristors and contactors, as depicted in Figure 9. When feasible, this system presents a cost-effective and space-efficient solution applicable to various heater types, as evidenced in Figure 10.

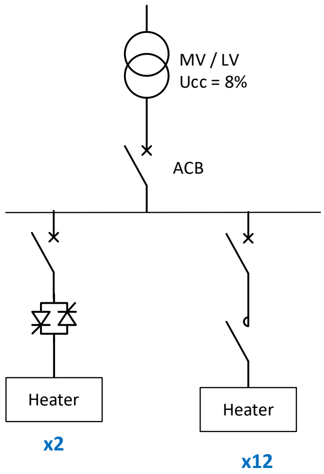

Fig 9: LV heaters controlled by a mixed of contactors and thyristors.

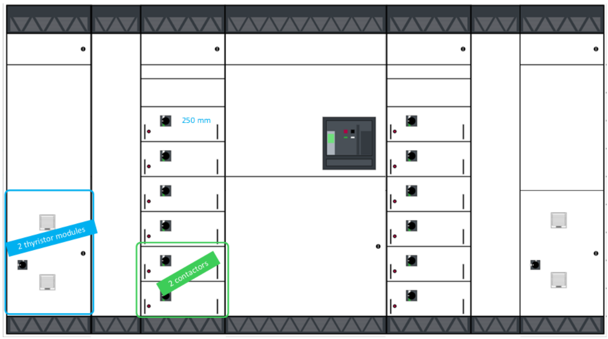

Fig 10: comparison of contactors and thyristors integration in a LV switchboard

D. Integrated Power and Process Approach for Electrification

Electrification entails a substantial shift towards electricity-powered process loads, necessitating deep integration between power and process systems within a facility. It is crucial to recognize that the characteristics of electric heaters and furnaces markedly differ from conventional fired heaters. For instance, electric heaters offer rapid ramp-up and ramp-down times, along with the capability for continuous adjustment to achieve precise power control, resulting in highly accurate temperature distribution.

An integrated power and process approach must be adopted throughout the facility's lifecycle, commencing from conceptual design, and extending into the operational phase. An integrated system eradicates the divisions between electrical and automation systems, providing a unified platform for process control and energy management. The convergence of automation and power serves to optimize process energy consumption, while the fusion of functional and electrical safety ensures safer operation of electrified processes. As the electrification rate increases within a facility, electrical system reliability becomes the foremost concern for operators.

The integrated power and process control approach yields a truly integrated plant control system encompassing process, safety, and electrical controls. Firstly, such a system eliminates interface barriers between the process and electrical control systems, allowing seamless and time-synchronized data sharing from a common source. Consequently, the integrated control system can timestamp alarms and events across various smart devices, IEDs, and specialized unit control systems, such as a turbomachinery control system. This feature significantly benefits operations and maintenance teams, enabling them to accurately track the sequence of events with millisecond precision and promptly pinpoint root causes during issue diagnosis and troubleshooting.[2]

Electric furnaces and heaters offer precise power and temperature control, particularly when employing direct heating methods. Leveraging this precision control and electrical instrumentation enables the monitoring and regulation of detrimental effects such as coking within furnace tubes. Moreover, it facilitates enhanced control over the composition, and byproducts from electrified process units. The system control must also adeptly respond to fluctuations in available power and adapt production setpoints accordingly.

Diverging from a conventional control system, the manipulating variables in an electrified process unit revolve around electrical system parameters such as voltage and frequency. In essence, the power system constitutes an integral part of the process itself. Consequently, the process control strategy integrates the power system as an embedded component, rather than treating it as an external system. Figure 11 illustrates an integrated power and process control system for an electrified process unit.

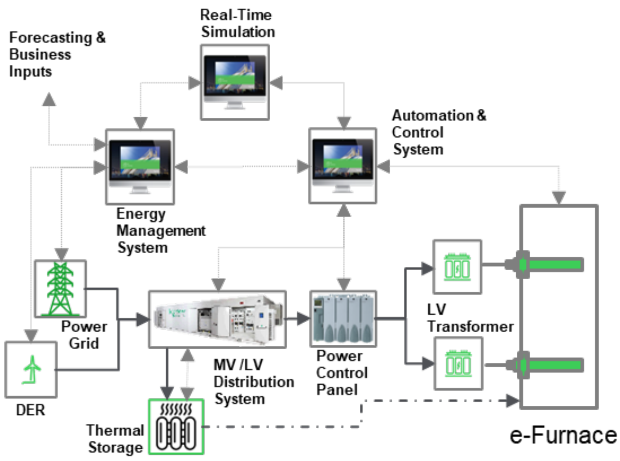

Fig 11: Integrated power and process control system architecture for process electrification

E. Clean Power for Process Electrification

One of the primary impediments to process electrification lies in the availability of clean power. While this remains a bottleneck in certain regions, this paper proposes an electrification strategy that incrementally raises the facility's electrification rate. Accordingly, diverse pathways exist to fulfill the facility's clean power requirements, leveraging a blend of procurement strategies and microgrid/DER technologies. Long-term PPAs stand out as a robust mechanism for securing sustainable energy. However, proactive measures are essential for operators to secure PPAs as they become available. Certain PPAs can integrate offsite generation with on-site generation, ensuring a dependable power supply for the facility.

Virtual power plants (VPPs) play a crucial role in securing the power demands of industrial facilities by integrating a network of distributed energy resources. By aggregating and orchestrating power generation sources, energy storage systems, and demand response measures, VPPs optimize energy usage and enhance grid stability. For industrial facilities, VPPs offer the flexibility to balance energy supply and demand in real time, mitigate peak load issues, and provide backup power during outages. This not only ensures a reliable power supply but also enables cost savings, improved energy efficiency, and greater resilience in the face of disruptions.

Microgrids integrating a mix of renewables and small modular reactors (SMRs) have the potential to evolve and meet the gigawatt (GW) scale power demand of industrial facilities. By combining intermittent renewable sources like solar and wind with reliable SMRs / linear generators, these microgrids can achieve a balance between sustainability and resilience. The renewables contribute to clean energy generation, while the SMRs / linear generators provide consistent baseload power, ensuring stability for industrial operations. Advanced control systems and energy management technologies orchestrate the optimal use of these diverse energy sources, enabling the microgrid to meet GW scale demands efficiently.

Energy storage systems play a pivotal role in supporting process electrification within the energy landscape. While battery energy storage systems (BESS) have garnered extensive attention in scientific and technical literature, their integration with virtual power plants (VPP) and microgrid systems has been widely acknowledged for ensuring the uninterrupted operation of downstream facilities. Nevertheless, given that over 70% of the energy demand in such facilities is ascribed to process heating, the significance of thermal storage systems cannot be overstated.

In downstream oil and gas facilities, thermal storage systems serve as a valuable component of the energy system, allowing the surplus electrical energy to be stored as thermal energy. This stored thermal energy can be effectively utilized for a spectrum of processes including heating, steam generation, and other thermal applications, thereby curtailing overall energy consumption and enhancing operational efficiency. Through the amalgamation of thermal storage with electrification, facilities can adeptly manage energy usage, mitigate peak demand, and optimize energy expenses.

IV. INTERSECTION OF ELECTRIC AND DIGITAL

The integration of electrification and digitalization stands as a powerful solution for decarbonizing downstream operations. Through digital technologies such as advanced analytics and machine learning, precise monitoring, control, and optimization of energy usage and production processes are made possible. This synergy enables industrial facilities to realize noteworthy energy savings, operational streamlining, and proactive environmental impact mitigation, thus driving forward the crucial objective of decarbonization. Notably, digital technologies play an indispensable role in three critical areas of the process electrification customer journey.

1) *Integrated Modeling and simulation of process unit electrification.*

As demonstrated in this paper, a crucial aspect in formulating an electrification roadmap involves comprehending the energy value chain and energy balance within the facility. This encompasses identifying bottlenecks in process design, power systems, electrical, and automation infrastructure. Additionally, these models must account for downstream market dynamics such as product demands, prices, and energy prices, alongside plant constraints. An integrated simulation platform becomes essential for concurrently evaluating process modifications and their impact on power systems and electrical infrastructure. It's important to note that every process design consideration significantly affects the associated electrical system, encompassing available power capacity, cabling cost, electrical equipment rating limitations, and short circuit capacity. Through an integrated digital simulation merging power and process design, designers gain the ability to directly compare conventional and electrified processes in terms of energy mix, carbon intensity, capital, and operational expenses, as well as technical constraints.

2) *Designing Flexibility for Electrified Processes*

The strategic design of plants with inherent flexibility, coupled with the implementation of adaptable operating procedures, plays a crucial role in effectively managing the fluctuations within the electricity market, encompassing both price variations and capacity dynamics. Flexibility is intricately woven into electrified processes through several avenues.

Operational optimization schemes dynamically regulate loads and production schedules in response to anticipated grid conditions and price fluctuations. Furthermore, the deployment of hybrid technologies, such as hybrid heaters offering fuel versatility (GH2, natural gas, electricity, or a combination thereof), and dual-drive compressors with the ability to switch between an electric motor or gas turbine, exemplifies the multifaceted approach to flexibility in electrified operations. Moreover, operating within an industrial cluster facilitates the aggregation and flexing of energy demand, presenting a viable strategy for navigating the evolving energy landscape.

The integration of real-time simulation into the control system is essential for the efficient operation of hybrid systems. The associated energy management system (EMS) serves as critical decision support, while real-time simulation enables the vital function of simulate-before-operate. This function considers real-time conditions of the process unit and power systems to predict the viability and effectiveness of the chosen hybrid configuration. Consequently, the electrified process unit can be operated with mixed energy systems concurrently with advanced model predictive control systems, ensuring optimized performance and reliability.

3) Multi Energy Management Systems

Process electrification represents a fundamental shift in the design and operation of process units, necessitating a holistic reconsideration of the overall system, encompassing energy systems, feedstock supply chain, and downstream product flows. The inherent flexibility of electrified processes, driven by substantial electric demand, underscores the mandatory need for adaptability. A comprehensive energy management system (EMS) stands as a pivotal component within electrified process plants. Leveraging artificial intelligence (AI), this system harnesses diverse data streams from process systems, planning systems, weather forecasts, grid, and utility forecasts, among others, to facilitate intricate decision-making processes. Through the integration of AI, the EMS executes complex decisions aimed at optimizing cost and carbon intensity while concurrently minimizing downtime and mitigating impacts on the power grid. By synthesizing and analyzing multifaceted data inputs, the system is empowered to make informed and strategic choices, ensuring efficient and sustainable operations within electrified process plants.

In full electrical or hybrid plants, the dynamic nature of renewable electric energy conditions, including price and capacity, presents a significant challenge for traditional process optimization systems. The rapid changes in the power grid necessitate an advanced approach to ensure optimal decision-making in real time. To address the limitations of current process optimization systems, a more effective approach leverages distributed Neural Network and parallel computing. By employing these technologies, faster computation is achieved, enabling the system to adapt to and make optimal decisions in response to the rapidly changing renewable electric energy conditions. The utilization of distributed Neural Network and parallel computing results in the system's ability to generate optimal decisions regarding the heating source and fuel with a high degree of confidence. This enhanced computational approach ensures that the plant can efficiently and effectively respond to dynamic changes in the power grid, ultimately leading to improved operational performance and reliability.

Process electrification demands a comprehensive approach to energy management, underpinned by AI-driven systems that can process and act upon diverse sources of information. The effective utilization of AI within the EMS enables the attainment of optimal cost and carbon intensity, while concurrently enhancing operational resilience and minimizing disruptions to the power grid.

IV. CONCLUSIONS

In conclusion, the electrification of downstream refining and chemical facilities necessitates a comprehensive systems approach that integrates design, operations, and the grid. This approach must align with decarbonization strategies, incorporate long-term PPAs, and consider grid resiliency. Internally, a robust energy management system assumes critical importance. The process electrification journey involves interconnected activities, demanding a systems design approach that encompasses electrified process design, electrical system design, and control and automation strategies. The integration of electrification necessitates an integrated power and process control approach throughout the facility's lifecycle. The availability of clean power, digitalization, and the intersection of electric and digital technologies play pivotal roles in enabling and optimizing the electrification process. This comprehensive approach ensures the successful and efficient transition toward electrification while addressing technical, economic, and environmental considerations.

V. ACKNOWLEDGEMENTS

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