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ENERGY SIMULATION TOOLBOX: ANALYSIS FROM PROJECT DESIGN TO RAILWAY OPERATION

CAJA DE HERRAMIENTAS DE SIMULACIÓN ENERGÉTICA: ANÁLISIS DESDE EL DISEÑO DEL PROYECTO HASTA LA OPERACIÓN FERROVIARIA

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Abstract

The commitment to the environment and climate change finds in rail transport lines a stimulus in the necessary social transformation. As an example, the 2030 Agenda of the European Union establishes clear objectives that are translated into courageous mobility plans and a commitment to research in the railway sector through the current Shift2Rail Joint Undertaking and the commitment to Horizon Europe as Europe's Rail, thereby a promising future is predicted for this sector.

The energy technology in the railroad is no stranger to these plans. Challenges for improving efficiency, quality and use of energy in guided transport systems are the challenges facing the present and future railway. To achieve a greater acceleration in the technological proposals that lead to a more rational, economic, and systematic use, it is essential to use computational modeling tools based on mathematical models that allow us to understand the behavior of the railway system operation in a reliable and economical term.

Thus, the modeling and simulation tools allow the calculation of the technical characteristics of the electrification system to adapt to the operational plans and the demand for services in the life cycle of the railway system.

Keywords: railway electrification, operational energy efficiency, electrical disturbances

Resumen:

El compromiso con el medio ambiente y el cambio climático encuentra en las líneas de transporte ferroviario un estímulo para la necesidad de la transformación social. A modo de ejemplo, la Agenda 2030 de la Unión Europea establece objetivos claros que se traducen en planes de movilidad valientes y una apuesta por la investigación en el sector ferroviario a través de la actual Empresa Común Shift2Rail y el compromiso con el programa horizonte Europa para el ferrocarril europeo, por lo que un futuro prometedor. se prevé para este sector.

La tecnología energética en el ferrocarril no es ajena a estos planes. Los retos para mejorar la eficiencia, la calidad y el uso de la energía en los sistemas de transporte guiado son los retos a los que se enfrenta el ferrocarril en la actualidad y para el futuro. Para lograr una mayor aceleración en las propuestas tecnológicas que conduzcan a un uso más racional, económico y sistemático, es fundamental utilizar herramientas de modelado computacional basadas en modelos matemáticos que permitan comprender el comportamiento de la operación del sistema ferroviario de manera confiable y en términos económicos.

Así, las herramientas de modelización y simulación permiten el cálculo de las características técnicas del sistema de electrificación para adecuarse a los planes operativos y la demanda de servicios en el ciclo de vida del sistema ferroviario.

Palabras clave: electrificación ferroviaria, eficiencia energética operativa, perturbaciones eléctricas

1. Introduction

An essential characteristic of the railway sector is to incorporate technologies efficiently in the face of safety and operational availability of the service. A significant contribution of computational methods is the help to make decisions at the design stage before trying to put them into operation, improving the treatment of the available information to generate valid hypotheses about future developments.

The experience of the Universidad Politécnica de Madrid, UPM, in public and private collaboration in railway research results in a toolbox to provide solutions that integrate the design of energy components, the safety of facilities and users, the verification of the efficiency of the system during the design and operation phases, even considering the integration of alternative and renewable energy sources, as well as the evaluation of electrical risks, network imbalances and electromagnetic disturbances on own services and adjacent to the railway system under study.

2. Electrification systems

An analysis of the public transport rail systems leads us to bring together the existing electrification systems in Europe, makes us believe that a valid tool for the main European electrification systems would require analyzing the differential possibilities of the flexible and rigid overhead contact line systems, to be able to operate in direct or alternating current systems of 1x25 kV at 50 Hz, 2x25 kV at 50 Hz, 15 kV at 16 ⅔ Hz alternative current.

An electric railway system comprises the service of the infrastructures from the following components: feeder stations that supply energy to the railway line; traction zones that delimit the area of influence of a power station and by self-transformation facilities (in the case of 2x25kV systems) as well as access points to own railway services, for example the stations:

The Feeder Station is located in the middle of the railway line in the case of alternating current or at the ends in the case of direct current. In 1x25 kV a feeder station covers an area of approximately 30 km. At 2x25 kV, the separation between these power stations reaches a nominal of 60 km(Friedrich Kiessling et al., 2018).

The function of the transition zones is to manage the control areas of each power station allowing a better operation of the railway service and its maintenance, being important in the case of alternating current because they separate the electrical phases in order to avoid short circuits.

In 2x25kV systems, the installation of auto-transformation distributed along the power line is carried out with the aim of reducing the return current losses and adapting the voltage supply of the 50 kV power station to the 25 kV necessary for the operation of the train. It also reduces electromagnetic emissions. The installation of one of these components is required every 10 km or so.

The energy to the train is transported through the overhead contact line component, which is flexible in open lines or rigid, at the discretion of the infrastructure manager, when we have an interurban or urban tunnel. In railway services, it is common practice to feed from this component the consumers of the rest of railway technologies such as signaling and communications through transformation points from the service value of the contact line.

3. Toolboxes focused on railway electrification

The technical and operational requirements of the service, among them the speed and the operation objective, as well as the verification of the limits and conditions of the technical standards and regulations are the answer that the set of tools involved in the design and verification of the rail power system.

In the scientific literature, general criteria for the dimensioning of the railway electrical system (Sanz Bobi, Juan de Dios; Jorreto Marcos, Federico; Garzón Núñez, 2007) have been described in which the limits of the technical regulations are considered to validate the basic parameters such as the admissible voltages for the electrical system, design of overhead contact line (CENELEC, 2019), the valid parameters for the interaction of the contact line with the train's pantograph (CENELEC, 2018), the value of the current that passes through each conductor or the verification of the power demanded by the trains with respect to the nominal power of the transformation groups of the feeding stations.

The tools that are described in this paper facilitate decision-making in order to have a viable and verifiable technological solution with the operation that covers aspects as essential as planning, sizing of facilities and checking the operation plans of the railway system; including those parameters that affect the energy value in train service or the validity of the designed system against the requirements of other technologies such as signaling and communications.

For this, different tools are available that allow the processing of solutions of the complete system or the individual study of components. To facilitate the processing sequence, a data model is made for the exchange between the modules, avoiding duplication of calculations or discrepancies between two parallel calculation systems.

The organization of the data has been done by identifying the constellation of actors that interact in the railway service: the information of the train units, the geometry and the profile of the track, the train dispatch plans and information on the technology of each component and subsystem of electrification on the rail system.

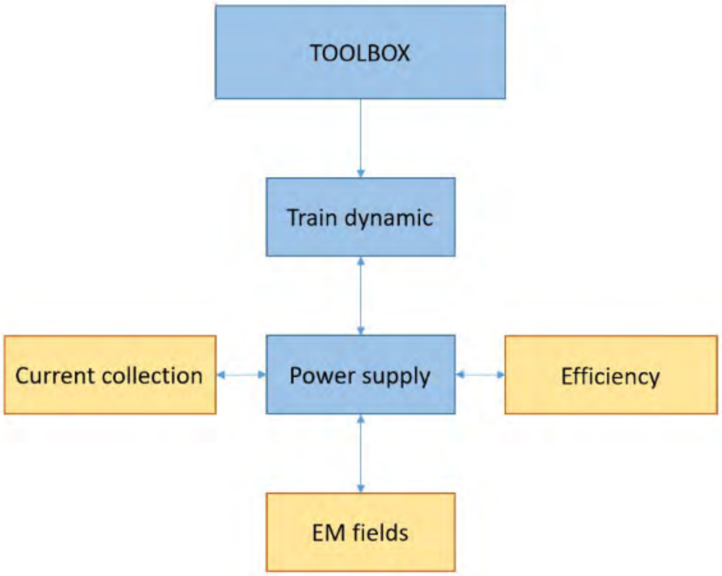
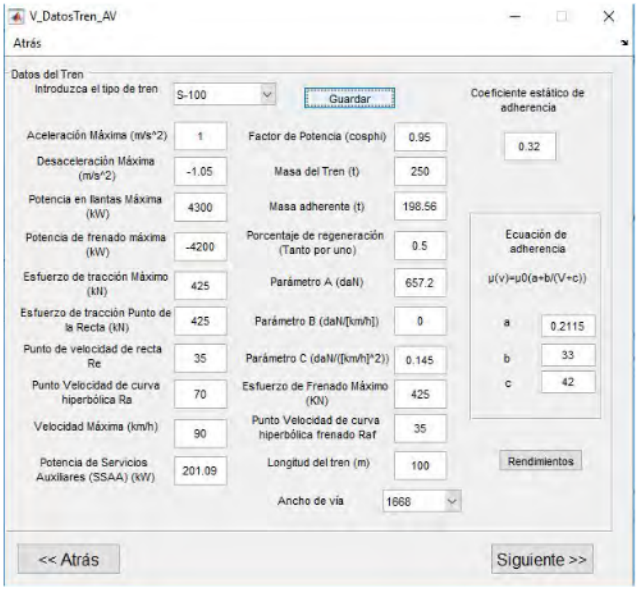


Figure 1: Toolbox structure diagram.

Three blocks are considered in the structure of the software: Train dynamic; power supply and current collection; and efficient and sustainable management.



Datos del Tren

Introduzca el tipo de tren: S-100
Aceleración Máxima (m/s^2): 1
Desaceleración Máxima (m/s^2): -1.05
Potencia en llantas Máxima (kW): 4300
Potencia de frenado máxima (kW): -4200
Esfuerzo de tracción Máximo (kN): 425
Esfuerzo de tracción Punto de la Recta (kN): 425
Punto de velocidad de recta Re: 35
Punto Velocidad de curva hiperbólica Ra: 70
Velocidad Máxima (km/h): 90
Potencia de Servicios Auxiliares (SSAA) (kW): 201.09
Factor de Potencia (cosphi): 0.95
Masa del Tren (t): 250
Masa adherente (t): 198.56
Porcentaje de regeneración (Tanto por uno): 0.5
Parámetro A (daN): 657.2
Parámetro B (daN/[km/h]): 0
Parámetro C (daN/([km/h]^2)): 0.145
Esfuerzo de Frenado Máximo (KN): 425
Punto Velocidad de curva hiperbólica frenado Raf: 35
Longitud del tren (m): 100
Ancho de vía: 1668
Coeficiente estático de adherencia: 0.32

Ecuación de adherencia

μ(v)=μ0(a+b/(V+c))

a: 0.2115
b: 33
c: 42

Figure 2: Example of toolbox interface (MATLAB)

Therefore, this toolbox can be defined as a complete simulation environment, flexible and capable of being applied in a multitude of scenarios, both in alternating and direct current systems, and independently of the catenary technology used since most systems are available through databases. There are additional possibilities of modifying the calculation bases to be able to apply them on specific scenarios and that differ significantly from those contained in the database.

4. Determinants of power consumption on the railway

The demand for electrical energy on a railway line depends on a multitude of factors, but the main ones are infrastructure, rolling stock and operation requirements.

Regarding infrastructure, this represents the main problem to be faced since the definition of the routes generally meets geometric criteria that do not always consider the future requirements of electricity demand. To address this aspect, which is presented as one of the main limiting elements different geometric characteristics of the track are considered especially curves and slopes.

Curves, especially those with a smaller radius, impose speed limits that will significantly affect the operation of train lines. These speed constraints also apply in other situations such as stations that generally have a lower speed stipulated in comparison with the rest of the route.

On the other hand, rolling stock is another factor that provides more constraints when calculating energy demand. This toolbox is characterized by considering a large number of determining factors in this field, such as the power curves in acceleration and braking, the comfort conditions with respect to acceleration, the regeneration and energy use factors in the transformation chains of power. The Davis curve of resistance is also taken into consideration, which presents in a simplified way the aerodynamic and rolling effects of the rolling stock.

Considering the service conditions, its general aspects are also taken into consideration such as the number of trains running through a station for each hour of service, the stoppage time at each station and the location of the stations.

With the data that have been described so far, the mechanical calculations are carried out to estimate the power required to move the trains under the service conditions considered. The data structure generated also makes it possible to know and assign the consumption made by each train at each moment, in addition to linking it to a specific position on the route.

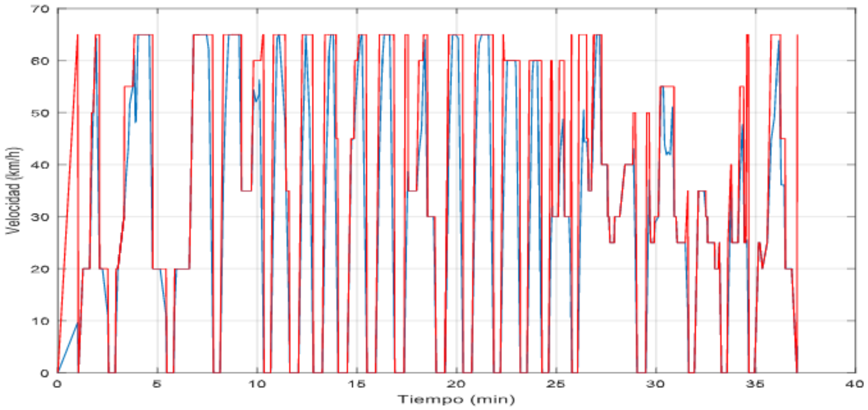


Figure 3: Train speed profile (blue) vs. maximum speed allowed (red).

Once the temporary, position and power assignments have been made, the electrical distribution can be calculated depending on the electrification system implemented, direct or alternating current, as well as the number of substations, their location and their supply capacity.

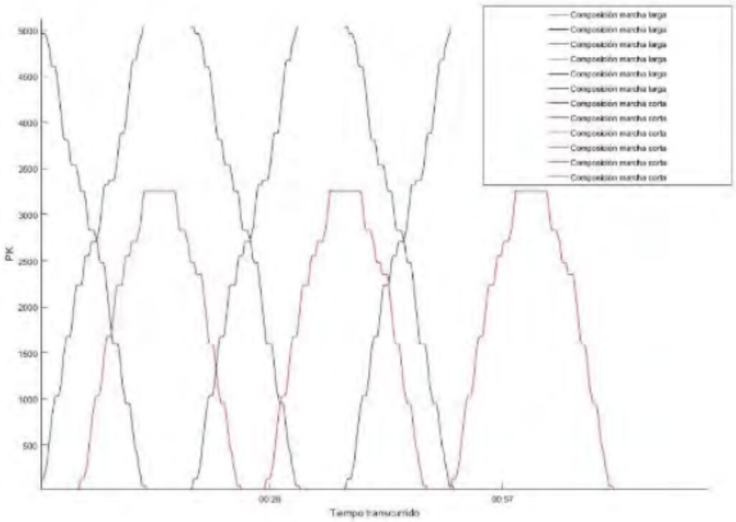


Figure 4: Example of operational condition in a railway line. Each line represents a train and its position against time.

The sum of all the defined actors and the temporal evaluation of each one of them makes it possible to calculate the current circulations in the supply and return systems. Results can also be focused on other conditions that must be fulfilled such as minimum accessible voltage on the overhead contact system or maximum value of current through wires (UIC 798).

The data structure mentioned above can now be applied in a similar way to substations, totaling the power that must be transformed and supplied to the system considering peak and average consumption values.

The result obtained allows making several analyzes on the design of the facilities, emphasizing that all these assessments can be made prior to the execution of the project, so they are presented at an ideal time for carrying out construction modifications, especially of those aspects that generate the most problems in terms of energy supply.

5. What if the design is energy deficient?

In this sense, the electrical circuits that make up the power networks may not be suitable and require elements such as feeders or the addition of more supply points. This toolbox offers the possibility of locating the points where voltage drops are excessive and that could compromise the operation of the railway system.

In the event that existing solutions are not sufficient and the installation of new supply points is required, a tool is also included simplifying the process of substation location. The result obtained through this option is a distribution of substations that makes it possible to cover the power demand on the line under specific operating conditions, also correcting the points where voltage drops can pose a problem.

One of the most important interaction links between tools that exist within this project is that the execution of the calculation for locate most suitable points for substations implies the iterative execution the dynamic distribution of loads in the circuit. This means that the result is a quality guaranty for the project, obtaining a valid solution without energy deficiencies.

6. How can electrical distribution be guaranteed?

Apart from the electrical section, the power distribution in electrified railway systems presents a mechanical determining factor. The current collection is carried out through a device generally known as a pantograph, located in the upper part of the rolling stock, which is in continuous contact with the overhead current collection systems.

This contact between elements, one fixed and the other mobile is essential for supplying the motors so it must be in accordance with the criteria imposed by the applicable regulations (CENELEC, 2012, 2018). These criteria mainly affect the mean contact force and the deviation of contact force from said mean value. The contact force between components directly conditions the area of conductive material through which the supply current flows.

Presented toolbox incorporates among its options a simulator of the dynamic behavior of the set formed by pantograph and overhead current collection systems. This tool is based on the execution and resolution of two significantly different problems at the same time, obtaining a valid solution for both.

The overhead current collection system is considered as a structure, on which the theory of structures is applied due to its special installation conditions. This theory considers geometric aspects of the components as well as their material composition. This way of defining the overhead current collection systems allows the application of the same method to different facilities, whether tram or high speed, including rigid catenary systems, generally installed in underground and metro lines.

On the pantograph side, a lumped mass model is used, which allows the dynamic behavior of the pantograph table to be reproduced reliably, reducing the computational requirements on this set of elements to the minimum possible.

The interaction between systems, like the general railway problem, resides in the synchronization of the contact point, so the Hilber, Hughes and Taylor algorithm turns out to be one of the fastest processing alternatives for the results. This algorithm also allows the resolution of the overhead current collection systems and pantograph matrices together, making it ideal for this problem.

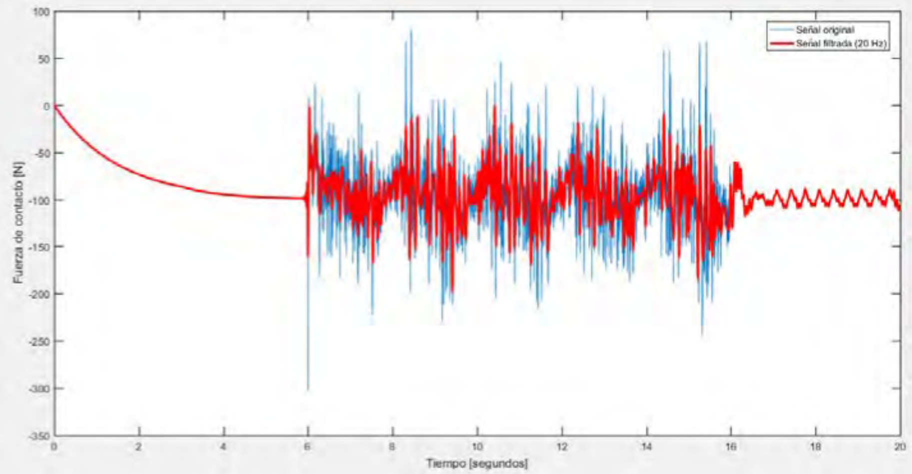


Figure 5: Dynamic force applied by a pantograph through a combined section of overhead contact line and overhead contact rail.

The result of these calculations is the profile of force applied by a pantograph on a contact line along the studied structure. Since the configurations of the overhead current collection systems vary depending on the infrastructure requirements, this type of simulation validates the installation of a specific set. The capacity to simulate different span configurations from the same tool for the same electrification system allows validating the complete infrastructure before its construction.

7. Is it safe to bet on electrification?

Railway is characterized by being a system focused mainly on safety, both for operations and for passengers and goods. The relationship of the railway with its immediate surroundings must also be considered, since due to the infrastructure requirements it can be especially invasive.

From this point of view, two differentiating aspects must be taken into consideration, on the one hand, the type of electrification, whether it is direct or alternating current, and on the other hand the potential at which it works, which also conditions the current flowing through the wires.

The problems of electrical networks with respect to their close surroundings usually appear due to conduction or induction, the latter directly related to electric and magnetic fields.

Conduction problems are more common in direct current systems, where any failure in the insulation of the rails can cause electric current to flow through the environment, outside the rail system. This toolbox considers these effects and includes a specific tool that allows assessing the amount of electrical current that reach ground in the event of a fault.

On the other hand, systems based on alternating current are characterized by using much higher potentials than direct current systems. This means that its presence in the environment generates an electric field capable of inducing electric currents on everything that is in its area of influence. Tools focused on induced on systems and structures are also included, in parallel and crossed lines, whether they are communication, track circuits or any electrical line, with the aim of reducing the effect of interferences related to electromagnetic fields. Furthermore, electromagnetic field density diagrams generated by railway installations can be generated based on the arrangement of the catenary conductors, so that in certain situations it can be evaluated whether an installation may be detrimental to another activity.

This toolbox commitment to security also includes those facilities on which it is directly dependent. Instantaneously high demand peaks that are not maintained over time characterize rail consumption. This means that conditions are variable in short periods of time. Within its capabilities is the assessment of the imbalances that can be induced in the general lines of electrical distribution and supply.

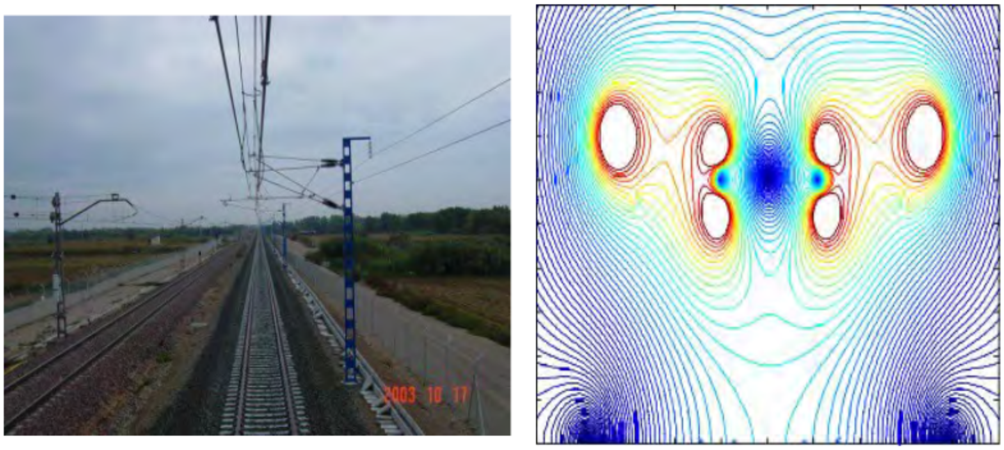


Figure 6: 2x25kV High-speed contact line and its magnetic field.

In general, tools integrated have led to an advance in the application of results obtained through dynamics and consumption simulators, to the calculation of the disturbances generated on the natural and technological environment of the railway. It has been possible to use a dynamic consumption scenario like the one described in previous sections for the evaluation of the inconveniences generated on the nearby environment by the installation of electrification systems.

8. What can the railroad do to improve?

It is evident that the evolution of technology makes it possible to improve current operating conditions, appearing attractive alternatives such as resorting to the use of renewable energies or the use of accumulators to take advantage of the energy regenerated by braking systems.

In this sense, described toolbox is ahead of its competitors by benefiting from the relationship between simulation modules. Obtaining dynamic and consumption profiles makes it possible to objectively evaluate whether the programmed operation of the trains is the best option. Current developments are focused on evaluating the movement of trains based on efficiency while maintaining compliance with the imposed timetable requirements.

These types of tools will allow to identify those areas where excessive demand is calculated for both acceleration and braking power. Once identified, alternatives will be valued making possible to take advantage of drift movements, that is, without accelerating nor braking.

Lastly, if the variation in driving conditions were not sufficient, an innovative tool that allows the evaluation of the installation of energy storage systems at certain points along the track is being developed. These energy storages would receive the energy recovered during the braking processes to supply it later when required in an acceleration process (Project, 2021).

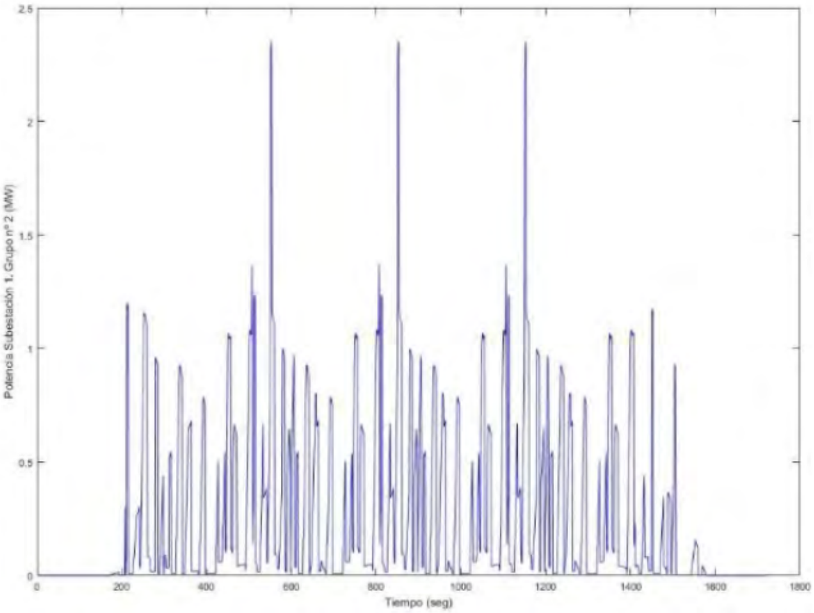


Figure 7: Example of power demand on supply stations.

9. Conclusions

The set of tools make up an application based on knowledge. This toolbox includes in its capabilities the study of the entire lifetime of a project, from its design to its start-up and operation. The main advantages provided by this type of tool is the crossing of data that exists between some simulation techniques and others, solving complex calculation environments which results are of great interest for the industry.

Acknowledges

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