Simulation and Optimization of Reversible Power Stations for Railway Applications

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***Abstract*— Regenerative Braking offers the possibility of recovering an appreciable quantity of for mission profiles that are associated to frequent braking and accelerations. Regenerative Braking is limited by the capability of the infrastructure of managing the energy regenerated by the train during braking. With conventional power stations the efficiency of regenerative braking is almost if there are no loads (as example an accelerating train) in the proximity of the regenerating convoy/rolling stock. This is difficult to be verified on lines with irregular traffic conditions or complex orography. Reversible Power Stations represent a possible solution since they allow a direct recovery of regenerated power by the infrastructure, but they involve an increased investment and complexity level. So, in this work it is presented a simulation tool that allow to optimize the disposition of reversible and conventional power stations along lines with relatively complex orography**

.Keywords—component, formatting, style, styling, insert (key words)

I. INTRODUCTION

Regenerative braking on railway rolling stock is a mature technology that can help to recover an appreciable amount of traction energy especially for mission profiles with frequent accelerating and braking manoeuvres such as in the case of local passenger trains, tramways, or metro-systems[1]. Otherwise, installation of reversible Power-Stations or wayside storage systems can be optimized to exploit positions along the line in which the probability of a regenerative braking of incoming trains is maximized[2]. Also, reversible Power-Stations[3] allows an easier management of scheduled timetables of trains along the line since allow the application of regenerative braking even in the absence of other trains to which recovered power can be transferred. Finally reversible power-stations can be also integrated in local smart grid contributing to an efficient reuse and sharing of regenerated power between different power sources and load such as example device for the recharge of electric road vehicles[4].

In this work authors propose a tool, developed in Matlab-Simulink, that allows to better understand the influence of key features (such as spacing between power stations, equivalent conductive section of catenary, line orography and corresponding timetables of trains) that should influence the choice between conventional and reversible power-stations.

II. MODEL DESCRIPTION

Proposed Model, developed in Matlab Simulink is composed by the following sub models where each number of the following list corresponds to the a corresponding block systems described in figure 1:

1. Train Behavior: power profile required by the simulated train can be calculated online or reproduced taking data from a previously recorded profile. Required power profile is associated to a train kinematics that is used to calculate the dynamic position of the train load along the line. The model is modular so it can be considered a single load or multiple traveling loads.
2. Load Positioning with respect to line infrastructure: once the position of train is known, this part of the program updates the corresponding topology of the equivalent circuit of the line (as example the distance of the load respect to substations and consequently the equivalent resistance of conductors).
3. Solution of the equivalent circuit: once the topology of the circuit is known, a solution is provided in the hypothesis of a DC system with pure resistive elements. These assumptions assure a very fast simulation of long missions corresponding to hundreds or thousands of kilometers of travelled distance. This approach grants an easy management of algebraic equations whose solution can be evaluated separately at each computational step with a symbolic/bondgraph approach that is often used, as example, in Modelica[5]. This block also verifies the existence of a feasible solution. This feature can be exploited to detect the instability of the proposed system respect to required power profile.
4. Conventional SSE: this an additional block that is used to improve the numerical stability of performed simulations when regenerative braking is applied under conventional/not reversible substations: reverse of current is held to zero adjusting the voltage level of the not reversible substation.
5. Blending between regenerative and rheostatic braking sub model 1 (train model) can calculate power flows due to traction and electric braking. However, when electric

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braking is applied both line and train equipment must be protected against over voltages that should arise if the infrastructure is not able to properly receive/manage incoming regenerated power. For this reason, if voltage V_c detected by the pantograph on the line exceed an assigned limit V_{limit} an increasing amount of power W_{el} (from electric braking) is dissipated (W_{dis}) on onboard resistors to limit line voltage to a maximum allowable limit V_{max}. So the regenerated power W_{reg} decreases as the voltage V_c increases. This behavior analytically described by (1) is also explained in figure 2.

$$W_{reg} = W_{el}\left(1-\left(\frac{V_c - V_{\lim}}{V_{\max} - V_{\lim}}\left(\frac{V_c - V_{\lim}}{V_{\max} - V_{\lim}} \geq 0\right)\right)\right)$$

$$W_{dis} = W_{el}\left(\frac{V_c - V_{\lim}}{V_{\max} - V_{\lim}}\left(\frac{V_c - V_{\lim}}{V_{\max} - V_{\lim}} \geq 0\right)\right) \tag{1}$$

6. Post-Processing: these additional blocks perform further analysis of results in terms of energy flows on different components.

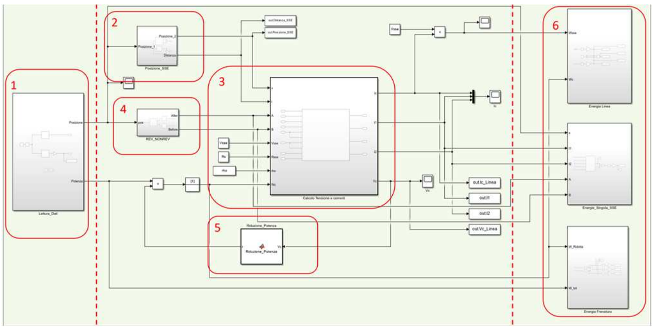

Fig. 1. Proposed Model, Simulink Implementation

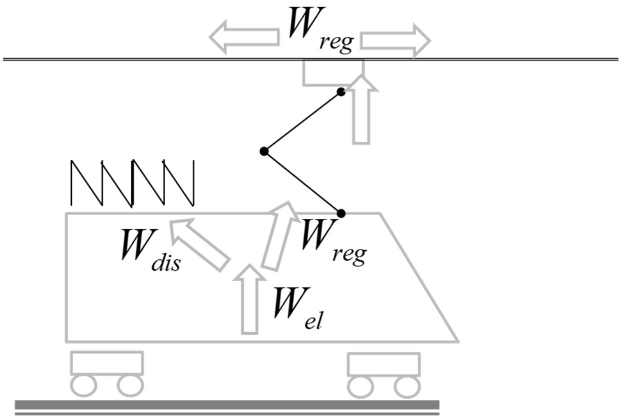

Fig. 2. Blending of Regenerative and Dissipative Braking

III. PROPOSED CASE STUDY

Proposed model is directly described and applied to the study potential advantages regarding the electrification with reversible or conventional power-stations of the Firenze Faenza line whose elevation profile is shown in figure 3. This benchmark test case was deliberately chosen to evaluate how line orography can influence expected mission profiles in terms of exchanged power flows. For what concern the simulated rolling stock it's considered the vehicle described in Table I whose feature are inspired to the Italian HTR 412. Since the chosen benchmark trains has only four coaches, it's considered the possibility of performing longer and heavier trains considering multiple composition in which 2 or 3 EMUs (Electrical Multiple Units). So, the same model can be used to simulated heavier trains reaching a max weight of 600 tons.

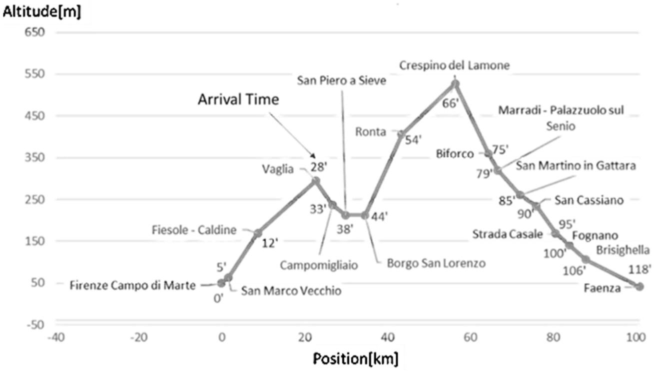

Fig. 3. Firenze-Faenza Line

TABLE I. DATA OF BENCHMARK VEHICLE[6]

PARAMETER	VALUE	PARAMETER	VALUE
Max Speed	160[kmh]	Capacity	300[seats]
Traction Power	1.325[MW]	Max Tr. Effort	160[kN]
Aux. Power	120kW	weight	200[tons]
N. Coaches	4	Eq. Inertia	210[tons]
Wheelset	B_0-2-2-2-B_0	El. Braking	40[%]
Multiple Compositions	X1(4coaches)	Brake Adh. lim.	0.15
	X2(8coaches)	Mech . Eff.	0.94
	X3(12 coaches)	Elettr. Eff. (stage)	0.94
Max Current	Dyn. 2000[A]	Electrification	3[kV]
	Standstill 200[A]	V_{max}	3900[V]
		V_{lim}	3750[V]

For what concern the electrification of the line it was supposed the possibility of varying several parameters such as:

- Equivalent Conducting Section of the line: sections of contact wires and ropes of the overhead line can influence the equivalent impedance of the line. A heavier catenary involves a better conductivity but also a higher construction and maintenance cost. In this work the considered equivalent conductive sections of copper are coherent with existing standardized catenaries [7] of Italian RFI (Rete Ferroviaria Italiana), corresponding values of corresponding resistances are shown in Table II:
  - 220mm^2 of copper, very light overhead line; the impedance of the rail is calculated considering a UIC 50 rail.
  - 320mm^{2}of copper, light line; supposed rails are UIC 60 ones.
  - 440mm^2 of copper, standard line; rails are UIC 60.

TABLE II. DISTRIBUTED RESISTANCES ALONG THE LINE

PARAMETER	VALUE	PARAMETER	VALUE
Res of 220mm^2 copper section	0,0818[Ω/km]	UIC 50 Resistance	0,0141[Ω/km]
Res of 320mm^2 copper section	0,0562[Ω/km]	UIC 60 Resistance	0,0118[Ω/km]
Res of 440mm^2 copper section	0,0409[Ω/km]		

- Spacing of Power Stations along the lines: power stations can be spaced at different distances along the line. In this work two values are considered 12.5 km and 17km.
- Reversible or Not Reversible Power Stations: conventional power stations are not reversible since passive rectifier are employed to feed the DC line. For what concern reversible substations different solutions and configurations are possible. For the proposed large-scale simulation, power stations are treated as ideal reversible/not reversible voltage generators with a series connected impedance. Some data and a simplified schemes are shown in Table III.
- Bilateral or Monolateral Configuration of Power Stations along the line

TABLE III. PARAMETERS ADOPTED FOR BOTH REVERSIBLE AND NOT-REVESIBLE SUBSTATIONS

PARAMETER	VALUE
Open Circuit Voltage	3700[V]
Output Resistances of the SSE	0.09[Ω]

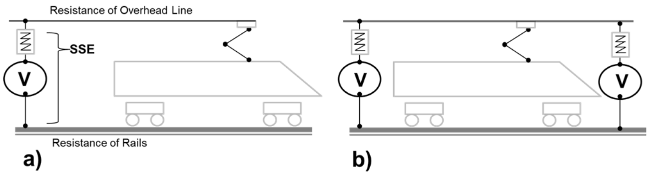

Fig. 4. Monolateral (a) and Bilateral (b) layout for powerstations along the line

IV. RESULTS

The simulation campaign described in previous section has been successfully performed. A first interesting result is represented by the computational efficiency of the simulation model that has been further accelerated using a RSIM target[9], to produce a further acceleration of the simulated mission which corresponds to a ratio between simulated time and duration of the simulation over 1000 even on relatively modest commercial laptop/notebook.

As shown in figure 5 The simulator can also reproduce the stops in the stations, this feature is useful to calculate appreciable energy consumptions in standstill conditions due to auxiliaries.

In figures 6 and 7 some results are shown: both figures represent the behavior of the overhead line voltage, measured on the train pantograph. Both simulations are referred to the same mission profile (from Florence to Faenza) considering a composition with 8 coaches (two EMUs assembled in a single composition). The simulated line has an equivalent copper section of 440mm^2 and the power-stations are spaced with a constant distance of 12.75 km with a bilateral layout. Figure 6 is referred to the case with reversible SSE, while figure 7 with non-reversible ones. In these examples it can be understood that even with reversible SSE and generous conductive sections of the line regenerative braking is able to produce a significant increase of line voltage (about 3800V) that should cause a modest but significant activation of dissipative braking on resistors (when the voltage reach 3800 V about a half of regenerated power is dissipated). Otherwise, as shown in figure 7, non-reversible power stations are not able to manage regenerated power during regenerative braking so voltage on the line sudden increase to the max level for with a complete rheostatic braking is applied stabilizing line voltage.

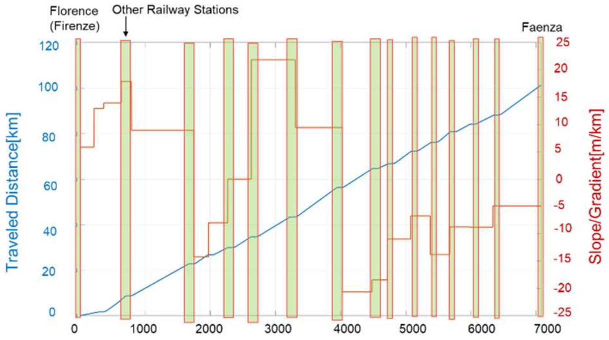

Fig. 5. Traveled distance and line gradient simulated during a forward run from Florence to Faenze

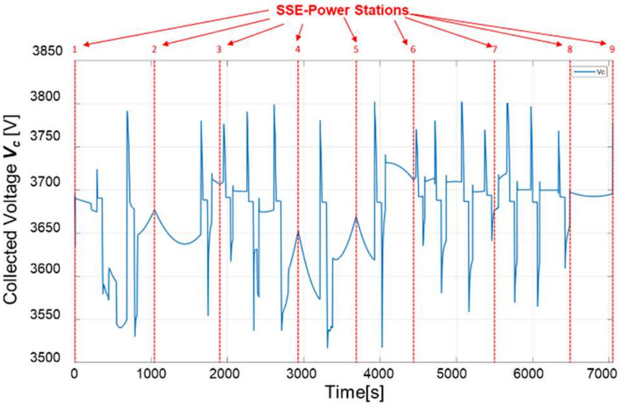

Fig. 6. Example of voltage measured at the pantograph (simulation) with reversible power-stations

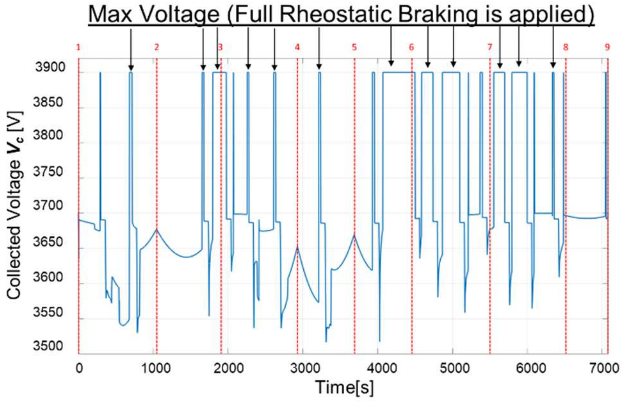

Fig. 7. Conventional/Non-Reversible Power Stations, example of voltage measured at the pantograph (simulation)

Further results in terms of collected currents are shown in figure 8: these results are referred to the same simulation scenario corresponding to simulated line voltages of figure 6. In this case it is shown the collected current I_c and the corresponding currents that are collected from the line in front (I_2) and rear (I_1) directions with respect to of vehicle motion. Proposed tool is substantially able di postprocess all the simulation data to calculate corresponding currents, power flows and losses associated to each power-station and each section of the overhead line (module 6 in the Simulink scheme of figure 1).

In this way it's possible to calculate the percentage of total consumed energy that is dissipated along the overhead line respectively for bilateral power-stations (shown in figure 9) and mono-lateral ones (shown in figure 10) where the following symbols are adopted:

- For the '*x*', abscissa axis the symbol *n*-C-*m* is adopted where *n* represents the number of car bodies/vehicles of the simulated composition. Otherwise the *m* number represents the equivalent section [mm^2] of the overhead line.

For the '*y*', ordinate axis the symbol *p*-*q* is adopted where *p* represents the distance between power station [km]. Otherwise, *m* is a string that is equal respectively to *irrev* and *rev* for non-reversible and reversible power-stations.

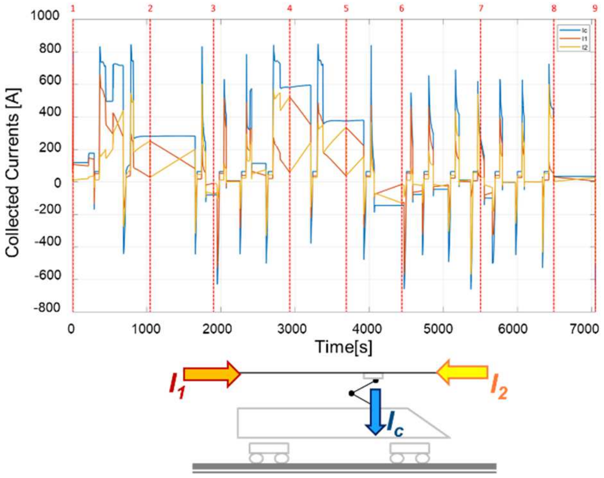

Fig. 8. Example of calculated current profile

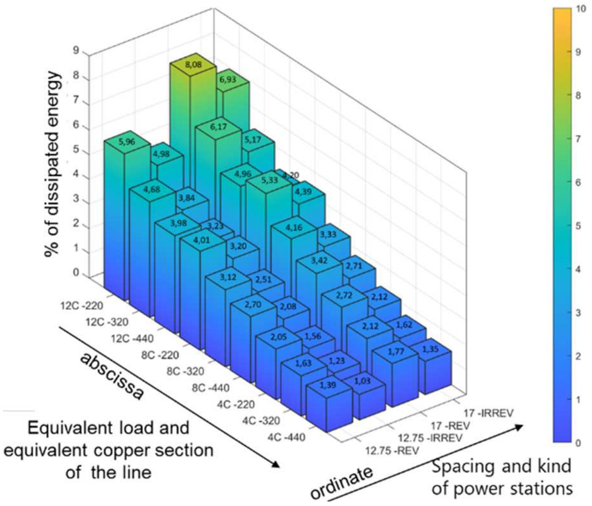

Fig. 9. Bilateral Power Stations, percentual losses on overhead line with respect to total consumed energy

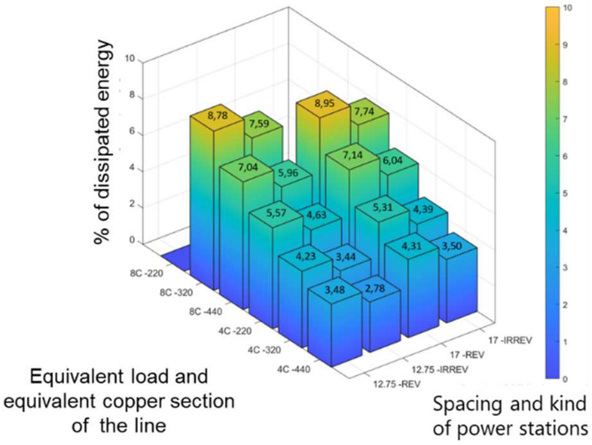

Fig. 10. Mono-lateral Power Stations, percentual losses on overhead line with respect to total consumed energy

Results of figures 9 and 10 clearly indicates that percentual conduction losses along the line increase proportionally to the distance between power stations and inversely with respect to equivalent conductive section. However, it's also interesting to notice some less intuitive results: longer compositions cause losses that are also proportional to train length/mass since losses increase at least with a square ratio with respect to collected power/current. Also, conduction losses are higher with reversible substations since also inverse currents during regenerative braking cause additional losses.

Also, as shown by figure 10 an increased length of the simulated composition involves a higher percentage of power dissipated on braking resistors of the vehicles, since higher regenerated currents produces a bigger overvoltage of the line. So according to (1) an increased amount of electric braking power is dissipated by on-board resistors.

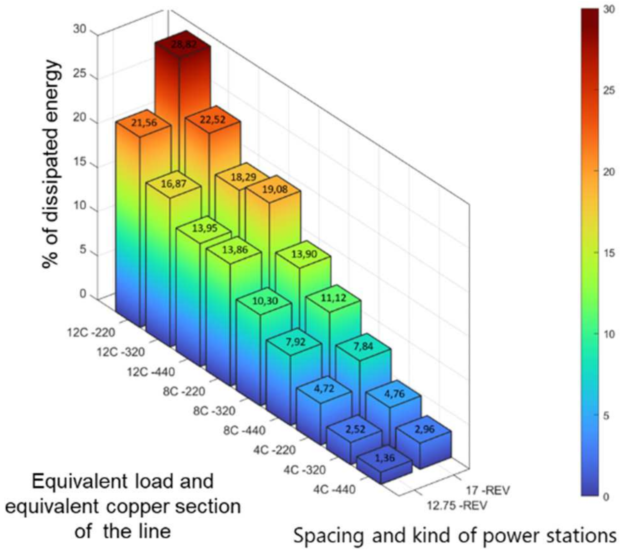

Fig. 11. Pergentage of dissipated power on braking resistor with respect to the total power produced by electric braking.

Once the losses on each subsystem are known it is possible to calculate the amount of energy that can be saved adopting reversible substations. As example in figure 12, it's shown the relative amount of energy that can be saved with regenerative braking adopting reversible power stations along the considered line. Results are referred to the composition with 8 coaches in which to EMU are coupled in a single composition of about 400 tons.

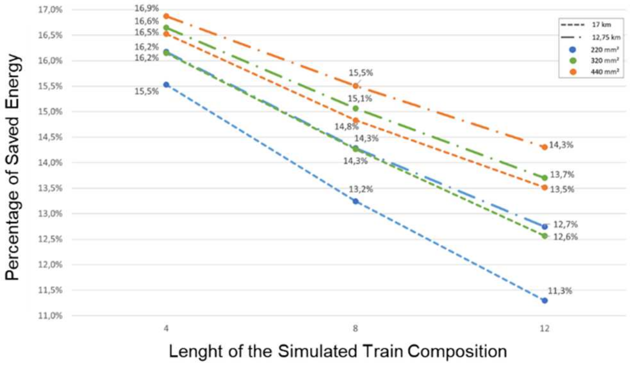

Fig. 12. Pergentage of saved energy with respect to the total consumed energy due to the adoption of reversible power-stations (bilateral layout)

The global calculation of saved energy for the whole line can be further refined considering the amount of saved energy on each power-stations. In this way it is possible to evaluate if in a specific location the installation of a reversible power station should be convenient respect to another location. An example of obtained results is shown in Table IV: the simulated train is a composition of about 400 tons (8 coaches corresponding to a composition of two coupled EMUs), equivalent conductive section corresponds to the standard value of 440mm^2[10] and bilateral, substations are supposed to be evenly spaced of 12.75kilometers. The same analysis is performed considering sense of motion of the train along the line.

TABLE IV. ENERGY CONSUMPTIONS AND SAVINGS ON EACH POWER STATION (400 TONS TRAIN

		SSE1	**SSE2**	**SSE3**	**SSE4**	**SSE5**	**SSE6**	**SSE7**	**SSE8**	**SSE9**
Firenze→Faenza[kWh]	Rev.	193	268	144	335	210	-1.1	36.6	45	6.3
	Non Rev.	197	277	176	347	234	77.6	85.9	63	10.2
Faenza→Firenze[kWh]	Rev.	-2.5	6.1	162	16	50.6	351	321	229	110
	Non Rev.	22	30.7	184	87.5	82.8	365	339	246	110
Roundtrip[kWh]	Rev.	190	274	306	351	260	350	356	274	116
	Non Rev.	219	308	359	435	317	442	425	309	120
Saved Energy [%]		13.2	11.1	14.7	19.4	17.8	20.9	15.9	11.1	3.5

The amount of saved energy is scaled with respect to the total energy delivered by each station, and it is calculated comparing the energy consumptions of passive nonreversible power stations with the reversible ones. Since scaled values should lead to some misevaluations (especially in case of stations subjected to different loading conditions), also the absolute amount of energy consumed in each scenario is shown.

some Power stations, such as example the numbers 4 and 6, the relative amount of saved energy with reversible substations is very high (about 20%). These relatively high savings are also registered in power stations for which highest values of consumed energy are recorded.

These results make these power stations potentially interesting candidates for the installation of a reversible power management system.

Otherwise for other power stations such as the number 9 the amount of saved energy is very small both in terms of absolute and relative evaluations.

Orography and altimetric profile of the line are key factors to understand why some sections of the line should be better suited for a reversible power handling since power stations 4 and 6 are localized along the line (see altimetric profile of figure 3) respectively near the stations of Ronta and Marradi where high gradients are also associated to the necessity of strong regenerative braking to stop the train in the station.

These large-scale evaluations of power flows of the line can be also used to preliminary evaluate sections of the line that should be affected by power transients that should be relatively more difficult to be handled by reversible power-stations.

These transients will be simulated again with a more detailed model of both overhead line (including power electronics and impedances) and vehicle traction circuits (probably limited to the first stage of converters with their resonating filters) adopting a proper integration step (10^{-5}-10^{-6} seconds) also considering the topologies of different kind of Power stations.

Finally another aspects related to the integration of the proposed simulation tools will regard the extraction from a large population of simulations of synthetic, probabilistic load pattern like the one that is represented in figure 13.

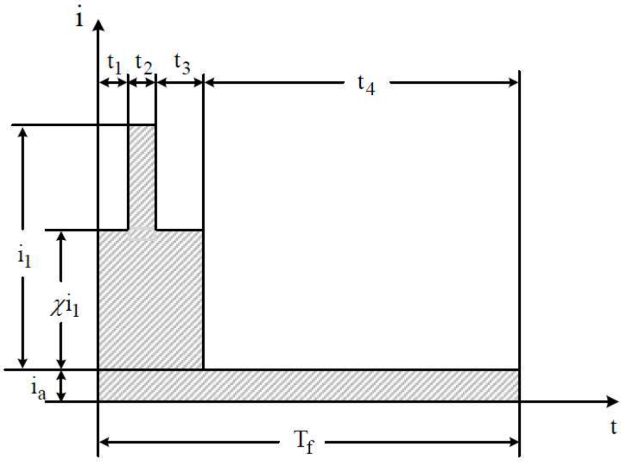

Fig. 13. Breaking down the absorbed current over time into discrete segments [12].

This representation encompasses three significant current values:

- a peak intensity i_1+i_a of duration t_2=γT_f for each segment.

- an intermediate intensity value Xi_1+i_a of duration $t_1+t_3=\delta T_f$;
- The current absorption of the auxiliary services, considered to be constant, with intensity $i_a=\alpha i_1$ and a duration of the idling time.

Starting from the "probabilistic method" or "Meregalli method," that was originally formulated in 1967 by Giorgio Meregalli, specifically for the operation of metro lines. In this method, any temporal arrangement of train positions is considered equally probable. With the proposed tools this probabilistic approach can be further improved by extracting refined probabilistic distributions of the loading conditions.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work, Authors have successfully presented a tool for the simulation of large-scale model able to properly reproduce power interactions between the train and power infrastructure allowing to analyze how different design parameters should affect performances of the system. The attention is focused on the proper choice of locations in which reversible substations should be more likely to be installed. Results are quite interesting confirming that an optimal layout must take count of altitude gradients and imposed trajectory that is often associated to fixed point along the line such as railway stations, signals, or other protected locations[11] along the line. Also proposed model is a good starting point for activities that will be completed within the National project that has financed this activity.

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