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Traction Power System Simulation in Electrified Railways
電氣化鐵道動力供電系統模擬

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Abstract: Electricity has been the major source of power in most railway systems. Reliable, efficient and safe power distribution to the trains is vitally important to the overall quality of railway service. Like any large-scale engineering system, design, operation and planning of traction power systems rely heavily on computer simulation. This paper reviews the major features on modelling and the general practices for traction power system simulation; and introduces the development of the latest simulation approach with discussions on simulation results and practical applications. Remarks will also be given on the future challenges on traction power system simulation.

摘要：電力是現今大部份鐵道系統的動力來源。可靠，有效率及安全的電力輸送對整體鐵道服務質素尤爲重要，跟其他大型工程系統一樣，鐵道供電系統的設計，運作及籌劃相當倚重電腦模擬。本文將回顧鐵道供電系統模擬的模型及一般常規，並通過模擬結果例子及實際應用，介紹最新的模擬方式發展。本文亦對鐵道供電系統模擬的未來挑戰作出評論。

Keywords: Electrified Railways, Computer Simulation, Traction Power System

關鍵詞：電氣化鐵道，電腦模擬，動力供電系統

1 INTRODUCTION

Electricity has become the primary source of traction power in modern railways. All metro systems are now operated by electricity in one form or another. While the diesel or coal driven trains are still heavily used in some countries, they are often limited to long-distance commutation and/or freight transportation. Electricity utilisation is the trend of rail transportation, just the same as for social advancement. Not only does it provide a reliable power source and enable robust train performance, it is also an environmentally friendly means to consume energy. Smoke and pollutants from combustion engines are simply not acceptable for operations in enclosed environment, particularly in metro systems. Eliminating the need to carry fuel on board may be seen as another advantage of using electricity for railway traction. However, the power distribution along the railway lines and the equipment to facilitate power transmission just pose another major engineering problem instead.

Indeed, the advantages of electric traction power do not come without a hitch. Electromagnetic incompatibility with the signalling systems was the early problem and is still raising major concerns. In some cases, physically separated systems for traction power and signalling have to be adopted, such as the 4-rail arrangement in the London Underground [1]. With advanced power electronics traction drive system, harmonics may be generated, which is significant enough to contaminate the electricity supplied to other users. Other concerns include safety (touch voltage on rails), operation (overloading, system fault and possible equipment failures), protection (lightning and vandalism), maintenance (rail corrosion due to stray current, pantograph and overhead line interaction) and planning (line extensions, shorter headway or higher speed).

With the inevitably high capital cost in a railway system, the study on traction power system starts from the design stage. Sizes and locations of the feeding substation and ratings of the power equipment to cater for the expected traffic volume are among the first questions from electrical engineers. Energy cost is also important for the operators in the negotiation of electricity tariff. The range of variations of power and voltage at certain points of the power network, robustness to absorb faults and capability to handle regenerated energy (from regenerative braking) are the key issues in operations. Further, the projected usage, as well as the possibility and extent of overloading, of the power system equipment, provides the useful information on maintenance work.

A comprehensive study on the traction power system has to be carried out even before the system is built. Computer simulation is conceived as the only viable means to enable such study. Simulations of different approaches and scales are used extensively to investigate various kinds of system studies. Simulation models and techniques on railway traction systems were first developed three decades ago. Since then, they have matured through a number of evolutions on model accuracy and computational efficiency and served the purposes of various applications for railway engineers, operators and researchers. However, the development of traction power system simulation seemed to come to a gradual halt ten years ago because of the saturation of application requirements. In recent year, driven by the increasingly demanding requirements on system reliability and availability, service quality and traffic demand from planning viewpoint and coupled with the possible need of real-time applications from operation viewpoint, new development in simulation approach and utilisation of advanced computing techniques have surfaced.

This paper aims to review the models, difficulties and applications of traction power system simulation. Comparisons are then made on the simulators with the traditional and the latest approaches of power flow calculation, followed by the discussions of incorporating the advantages of modern computing hardware and software to enhance the applicability of the simulators.

2 TRACTION POWER SUPPLY SYSTEMS

The traction power system is, in its simplest form, a huge electrical circuit. The power supply may be in single or multiple sources and the feeding arrangements vary in different systems. The complications, as illustrated later, mostly come from AC traction power supplies. The loads in the electrical circuits are the trains which are moving and demanding different levels of power according to their operational modes and speeds. A train may become a source if regenerative braking is allowed.

In order to attain steady-state solution of the electrical circuit, the sources, feeding networks and loads must be properly modelled, which is no simple task, given the varieties of supply systems and operation conditions. This section examines the features of traction power systems and discusses the considerations and difficulties in modelling.

2.1 Power Supplies

2.1.1 DC supplies

DC railways are operated at relatively lower voltages. 600V, 750V and 1.5kV are the typical figures [2]. The DC traction power comes from trackside rectifier substations linked to the AC distribution network. Each feeding substation covers a section of track but there is normally no isolation between adjacent sections, which implies a multiple-source system. The section length is substantially shorter because of the lower distribution voltage level. It should be noted that the traction current can be as high as a few thousand amperes. Overhead catenary or a third rail (or even trackside sliding contact), with running rail return, is employed to distribute power to trains. Fig. 1 shows a typical DC supply network for a branched two-road service. Switchgear and isolators on AC side and circuit breakers on DC side are installed for protection and fault management.

DC railways are usually less susceptible to electromagnetic interference even though harmonics from the rectifier substations or traction equipment require proper filtering. Leakage current through the running rails however causes corrosion on the rails. The rail-to-earth conductivity, which determines the amount of leakage current, depends on soil properties and the earthing structure in the surroundings. The high return current through the rails also develops voltage on rails, which may be hazardous to personnel working close to the rails.

Despite being a multiple-source system, DC traction power system does not cause too many difficulties to the solution calculation process in simulation (trains may become sources with regenerative braking to turn the circuit into a multi-source system anyway) because of the simple feeding arrangement. When the locations of trains and resistance of rails and overhead cables are known, it is only tedious to establish the electrical circuit in order to solve for the voltages and currents in the circuit. Branches and multi-track lines are common in railways and they just make the electrical circuit more complicated. Appropriate network partitioning will certainly reduce the computational demand of the solution process.

As some substations are equipped to receive power from the DC system and release it back to the AC side so as to absorb the excessive fed-back energy from regenerative braking, the bi-directional flow of power should be incorporated in the models. However, the important feature is that receptive substations allow power flow in one direction (from AC to DC) most of the time and they only permit reversal of power flow when it is necessary.

2.1.2 AC supplies

Power for AC railway traction is obtained from utility supply system, at transmission or sub-transmission voltage level, through traction feeding substations. 25kV traction network at 50 or 60Hz is the most commonly adopted system. The rail line is usually divided into a number of isolated feeding sections and each section is fed by a single-phase supply from a transformer within the section. Power is carried to the trains through overhead catenary and current takes the rails as return paths. High catenary voltage allows lower traction current and smaller power loss while the section length (or distance between adjacent feeding transformers) can be kept relatively long, typically over 10km. Adjacent sections are supplied by different phases of a 3-phase network and they are separated by track neutral. Provisions of isolators and switchgear are necessary for track neutral and parallel sections to enable continual feeding in cases of failures and outages by isolating certain faulty equipment or section or even reconfiguring to a different feeding network.

A number of feeding arrangements are available, including direct supply with or without return conductors, booster transformer (BT) and autotransformer (AT) systems. Several considerations, such as power transmission efficiency, voltage regulation and interference suppression, have to be taken on the adoption of the suitable feeding arrangement for a particular traction power system.

Direct connection of the transformer secondary to the catenary and rails is the most straightforward means of power feeding. Significant rail-to-earth leakage current is the major drawback of this feeding arrangement because of the inevitable rail-to-earth impedance. Corrosion on rails is no longer an issue because of AC current. However, the imbalance between the supply current on the overhead cable and the return current on the rails (the difference between the two being the rail-to-earth leakage current), coupled with the physical separation between overhead cable and rails, is often one of the main causes of electromagnetic interference to the lineside telecommunication equipment. As shown in Fig. 2, the addition of a return conduction, in parallel with the catenary and connected to the rails at regular intervals, helps reduce the leakage current, but only to a certain extent.

BT feeding provides another means of interference reduction by forcing the current to flow in the return conductor rather than in the rail. However, it is at the expense of poorer voltage regulation because of additional impedance of BTs. Having allowed power to be transmitted at the voltage twice as high as the operating voltage, AT feeding improves system efficiency. Interference suppression is another advantage of AT feeding. In addition, AT feeding provides better voltage regulation and allows longer interval between transformers [3], which is essential for service reliability of long-distance rail lines, if not just the capital cost. Both BTs and ATs are placed at regular intervals within a feeding section. Illustrated in Figs. 3 and 4, BT feeding operates by balancing currents on the two windings of the transformers whilst AT relies on voltage balancing. By introducing BTs or ATs within the feeding section, the current is forced to return via the return conductors. Such manipulation of current return path is however at the expense of more conductors (mostly overhead) along the lines and more complicated current distributions.

The additional equipment with BT and AT feeding presents extra modelling works in the simulation. The electrical parameters of the equipment are often available from manufacturers or operators but they have to appear as complex numbers (e.g. impedance instead of resistance) because of the AC nature. The scale and complexity of computation required is then inflated significantly. It is also necessary to examine the current distribution in the conductors along the line as the mutual impedances among the conductors, as well as the admittances to the ground, play important parts in the steady-state solution. Train position relative to the locations of BTs or ATs holds keys to current distribution and different train positions may lead to different circuit configurations. One consolation from modelling viewpoint is that the feeding substations here are not interfaces between AC and DC systems, as in DC railways. The complication of power flow direction does not exist in AC supplies even with excessive power recovered from regenerative braking.

2.2 Loads

In a typical inter-station run, a train accelerates from a station to the maximum permissible speed, maintains the speed and brakes to a complete stop at the next station. It therefore goes through a wide range of speeds, different operation modes and hence the power demand may vary significantly within a short period of time. Train speed and operation mode are the decisive factors of the immediate amount of power required by the train as a load. They are however determined by the traction equipment characteristics, train weight, aerodynamics, track geometry and drive control. The electrical representation of the trains in the circuit as a variable load (and sometimes source) requires careful modelling in the simulation.

With the moving trains, the configuration of the electrical circuit keeps changing and the solution relevant to one instant may not be valid to the next. If it is necessary to attain the details of the traction power system behaviour and train interaction, the electrical circuit has to be updated and the new circuit solution is to be re-calculated at every regular time interval over a long span of time. Train movement simulation is the basic accompanied function to provide train position, speed and operation mode for the purposes of establishing the electrical circuit. The power network solution process, usually with manipulation of large-scale matrix equations, at each time interval thus imposes tremendous computational demand to the simulation. In fact, the power network solution is always the most time-consuming step of a whole system simulation in railways [4].

3 MODELLING

This section discusses the features in the traction power simulation models which require careful considerations.

3.1 Power supplies and feeding networks

3.1.1 DC supplies

The power source at the substation is assumed to be a constant (usually voltage) source with equivalent source resistance. When the power system calculation does not come up with a solution because of excessive over-voltage at the substation or current flowing in opposite direction (usually resulted from regenerative braking), the substation may be re-modelled as a passive load to allow power to go back to the supply system, provided that the substation is supposed to be capable of doing so.

Once the train positions are known, the resistances between trains are those of the overhead lines (or contact wires) and the rails separating the trains if the resistance per unit length of these conductors is assumed to be constant. In practice, the resistances of the conductors are current-dependent [5] even though the variation is not disproportionate. Such dependency can be incorporated in the simulation model for better accuracy but the solution process may take more time with more iterations.

Rail-to-earth leakage current is another issue leading to complication. The leakage is a distributive phenomenon along the rail and it can be modelled with a finite-element approach, in which the rail is divided into a number of elements of equal length and a certain portion of the current flowing through each element leaks through the rail-to-earth resistance while the remaining carries on to the next element. As a result, the rails have to be represented by a number of resistances in series, instead of one resistor only, intersected with the rail-to-earth resistances in between. As rail-to-earth leakage current does not directly affect train interactions through the power system, the justification of its inclusion in the simulation model is thus determined by the applications of the simulator.

3.1.2 AC supplies

Feeding substations are still modelled as constant voltage sources. Additional conductors (mostly overhead) and lineside equipment (BTs or ATs) can be represented by appropriate impedances and mutual inductances in the electrical circuit. However, the modelling of the mutual induction among the parallel conductors requires the finite-element approach again. The physical sizes, relative resistivity, permeability and geometry of the conductors, relative permittivity of the medium, current distribution and earthing conditions are essential in this multi-conductor model [3]. Further, as the rail is of unique shape, calculation of impedance, which is current and frequency dependent, is far from easy. It can be treated as a single cylindrical steel conductor, upon substantial pre-processing computation, with different cross-section areas for a wide range of frequencies [5]. Rail-to-earth leakage current can be conveniently included in this finite-element approach, which is a bonus. With the distributed elements, the number of components in the electrical circuit becomes very high and the circuit is quite complicated even before the trains are inserted.

In order to reduce the scale of computation required, conductors with the same longitudinal voltages can be combined (e.g. the two rails) as one. There are still at least three along-the-line conductors with BT and AT feeding, as shown in Figs. 3 and 4.

3.2 Loads

Trains, as loads, can be simply modelled as passive and power-consuming elements in the electrical circuit to represent its function as a power sink. In the case of AC railways, the load should consist of the resistive and reactive components to illustrate its power factor. However, such simplicity does not reflect the dependence of power demand on train speed and operation mode, as well as voltage-sensitive nature of the load.

One approach is to derive the train current and traction effort required, given the train speed and operation mode, from the traction equipment characteristics (available from the operators or manufacturers), followed by establishing a voltage-impedance (Thevenin equivalent circuit) or current-admittance (Norton equivalent circuit) model [6], which is piecewise linear. The equivalent circuit may contain a hypothetically negative impedance to indicate the power-sinking property of the load. Detailed traction equipment characteristics containing traction performance within a range of voltage variation can be adopted to model the voltage-dependent performance of the load. The data are usually made ready prior to the simulation and stored in the simulator as look-up tables for easy and time-efficient referencing.

Another approach is to work back from the output mechanical power. From the required traction effort to sustain a certain speed or to produce acceleration, the output power can be calculated from the train weight, track geometry, other train movement parameters and power losses. Given the efficiency of the traction system, the input electrical power is attained and an equivalent circuit with respect to the power demand can again be used to represent the load. It is a simpler approach but it relies on comprehensive modelling of all possible power losses during train movement.

3.3 Power network solution

With the models of power supply and traction equipment available, the circuit of the electrified railway line is established for the calculation of voltages and currents at various points of interest. The most direct approach is to formulate a matrix equation from the electrical circuit using either mesh or nodal analysis [6]. The solution is attained from solving this matrix equation whose coefficient matrix size depends on the number of trains and complexity of the network. This approach is more suitable for complex electrical networks because it is often easier to identify nodes than loops in non-planer networks. From a programming perspective, automatic network set-up procedures and advanced network graph techniques are desirable in the implementation, with the use of the nodal approach.

The coefficient matrix in the power network solution is sparse, banded and symmetric for a simple two-track network. When the network consists of branches and loops, the bandwidth of the coefficient matrix increases and the sparsity deteriorates. Fig. 5 shows the circuit representation of a typical DC traction power network with branches. It is not difficult to see that the railway traction power network is characterised by sections of ladder type networks infrequently cross-connected. For this characteristic topology, the sparse matrix technique coupled with efficient matrix elimination methods leads to an expeditious network solution, since it does not suffer from the fill-ins that the direct inversion of the coefficient matrix requires. It has to be stressed again that if the finite-element approach is adopted to model the conductors, the electrical circuit network will be further complicated and the size of the matrices will be driven up considerably.

With the coefficient matrix being positive definite (PD), symmetric and sparse, many sparse matrix elimination techniques tailored for PD matrices, such as LL^T decomposition and Cholesky decomposition, are applicable. For sparse matrix solution techniques, the essence is equation-ordering. There are generally two types of ordering methods namely, static and dynamic ordering. Typical examples of static ordering for long and thin ladder type networks include the Cuthill and McKee algorithm [7] and reverse Cuthill and McKee algorithm [8], which make use of the property that the zero elements situated before the first non-zero element on any row always remain zero. For dynamic ordering, the minimum degree algorithm provides an efficient alternative for solving the network matrix. This is actually a heuristic algorithm to find an ordering for the coefficient matrix which suffers from low fill-ins when it is factored. The minimum degree algorithm is particularly suitable for solving medium to large networks, in which there are 200 nodes and more. For smaller networks, the minimum degree algorithm becomes a less efficient option since a significant portion of the overall processing time is used in the symbolic factorisation process.

Partitioning the electrical network into several smaller, more manageable sub-circuits by node splitting [9] is one of the common methods to enhance simulation efficiency. This technique, also known as diakoptics [10], involves tearing a given network into a number of independent parts and putting the solutions of the divided parts together to form the solution of the original problem. The natural tearing points in traction power network are the branches because the coefficient matrix of an isolated branch is highly sparse. However, the number and size of the torn parts depend on network topology and number of trains on the branches respectively [11].

3.4 Integration with train movement

Traction power system simulator only provides a steady solution for a given train condition. In order to establish voltage and current profiles over time at certain points of the power network while trains are moving in the railway system, it is essential to integrate the traction power system simulator to a train movement simulator.

Taking into account the track geometry, signalling constraints, timetable or headway conditions, traction equipment behaviour and civil engineering speed restrictions, a train movement simulator derives the speed, position and operation mode of each train at each and every specific time intervals. One of the key factors in train movement is inevitably the tractive effort produced by the traction motors. Performance of the traction motors is a function of train voltage and current which are in turn calculated by the traction power system simulator according to train speed, position and operation mode. As a result, interactions between power system and train movement simulator are necessary for the consideration of dynamic train behaviour.

4. SIMULATION AND APPLICATIONS

Two simulation approaches on the models described are discussed here, one with the traditional concept of deterministic calculation and the other with a new method of probabilistic calculation which provides an alternative prospective. Some examples of simulation results are shown here to illustrate the differences in their functionalities. A number of applications of traction power system simulation are then given to demonstrate its value in practice.

4.1 Deterministic simulation

In most applications on operation and design, the full details of interactions among trains through the traction power system and between feeding system and trains are called for. Simulations under different operational conditions and traffic demands (or ‘what-if’ scenario studies), including normal and extreme, are required. Comprehensive models with the considerations stated in the previous sections are required in the simulation and the network solution, however tedious, is attained deterministically with respectable accuracy.

Traction power system simulation is time-based and accompanied by a train movement simulator. From all last known train speeds and positions, the power system simulator establishes the power network with respect to the train positions, track layout and feeding arrangement; and solves for the voltages and currents for one time step. With the train voltages and currents passed back to the train movement simulator, it calculates the next train speeds and positions. The process then repeats at every time interval. This repetitive interaction between the power system and train movement simulators is illustrated in Fig. 6. Software implementation is quite straightforward but still tedious. Nonetheless, systematic data management and substantial amount of data storage are strongly required.

Figs. 7 and 8 show the sample results of voltage and current variations at a feeding substation in a typical DC metro line with nominal voltage of 1.5kV. They indicate the loading at the substation at a particular traffic condition, and peaks and ranges of variations can be identified easily. Figs 9 and 10 illustrate the voltage and current of a train as it moves along the line and they allow monitoring of the train power demand. The results from the power system simulation always correspond to the train movement. For example, current peak and voltage dip indicate accelerating train whilst a train in regenerative braking is reflected by negative current flow and voltage rise.

The outcomes from the power network simulator are the exact voltages, currents and power flow profiles at all crucial points in the network at every time step over a period of time. They are proven to be very useful for power engineers, railway operators and maintenance personnel alike. However, as the results come from time-consuming calculations and the output data is often voluminous (with the size of the power network and number of trains) for analysis, not to mention the possibility of further processing and storage, detail redundancy, though an advantage at times, is a drawback of this deterministic approach for certain applications. Even though the results give detailed account of the electrical behaviour of the power systems and trains, it has to be said that not every detail is required in most applications.

Most of the existing traction power system simulators [6], [12-15], as well as other commercially available packages [16], employ this deterministic approach. They are also equipped with reasonable user interfaces to enable the input (and output) of the vast amount of data required for (and produced by) the simulation. Nearly all of them have been tailor-made to suit the purposes of particular systems or specific studies and hence some of them may not be properly documented in public domain.

4.2 Probabilistic simulation

A newly developed alternative is a probabilistic approach in which the outcomes are probability density functions (pdf) of voltage or power flow at certain points of the power system, indicating the ranges of variations of such parameters and hence the loading conditions, on probabilistic basis with a simple and holistic representation, while skipping the tedious process of extracting the required data from huge amount of simulation results. However, the traditional traction power simulators by deterministic approach are not to be replaced by those from this probabilistic approach. The probabilistic approach indeed provides a different viewpoint of insight into the traction power system behaviour and hence suits different purposes of applications.

To build the necessary pdfs, train position is the starting point and its own pdf is established from typical speed profiles of inter-station runs [17], which can be generated by an off-line train movement simulator. The random sample drawn from the train position cumulative probability function is used to deduce train speed and operation mode, and hence the train power demand is derived from the traction equipment characteristics. With the loading conditions (trains) known, the power network is solved to produce the voltage, current and power flow at certain points. The process is repeated with sufficient number of random samples of train position and the resulting pdfs are formed in Monte Carlo simulation technique. The process is summarised in Fig. 11. Multiple trains of specific timetables (or headways) are put into the calculation according to their supposed separations so that the effects they impose on each other can be incorporated [18].

As there is no direct interaction between train movement and power system simulators in this approach, the exact detail of the relationship between train voltage and speed may not be fully reflected. Again, the purposes of the application decide the level of details in the output, and thus the simulation approach to be adopted

The results from this approach basically give the same information on the traction power system behaviour over a period of time as in the deterministic approach and they rely on the same modelling considerations in the calculation. The main difference is in the formats of output presentation. As shown in the sample results presented here, the sizable data on the variations of a circuit parameter (voltage, current or power flow) is capsulated in a single graph of probability density function whereas the details of exact value at a specific point of time are hidden. Despite the different interpretations of output, computation demand on traction power system simulation is however very much similar in both deterministic and probabilistic approaches. The general experience in this approach is that the Monte Carlo simulation requires at least 10,000 samples to establish reliable pdfs.

Probabilistic approach is not yet as commonly adopted as the deterministic one but it serves its purposes as a supplement to the former. Figs. 12 and 13 are examples of voltage and power demand pdfs of a train in an AC railway with AT feeding. With a nominal supply voltage of 27.5 kV, the voltage spreads over both sides of the nominal value (and power pdf spilling on both sides of 0MW), which indicates that regenerative braking is allowed. Figs. 14 -16 compare the power demand pdfs at a feeding substation under the same traffic conditions with the three different feeding arrangements. AT feeding, as expected, provides better voltage regulation with a narrower spread in the pdf.

4.3 Applications

There have been numerous practical applications of traction power system simulation. Even though the objectives of the applications may only focus on a particular aspect of the power system, the simulation of the whole system is usually needed to facilitate the full functions of the aspect in question. System sizing on equipment and components is an indispensable step in the design stage. As each railway is unique in its traffic demand, track geometry and operation, tests on power rating limits or capacities [19] and claimed performance [20] with respect to the characteristics of the railway system are compulsory even before procurement of the major equipment of the system. Unsurprisingly, whole system performance analysis with complete incorporation of train movement simulator [21] to examine the compatibility among different sub-systems, as well as their own functionalities, is always one of the main purposes of simulation. While a full system analysis warrants simulation of deterministic approach, the uncertainty on some system parameters at early stage of planning may find the probabilistic approach more suitable.

Dynamic behaviour of the power system in the course of operation is another major topic of interest. As voltage stability is vital to consistent train performance, a number of studies have investigated voltage fluctuations in different systems [22-24] under various operation conditions. Applications, such as studies on stray current [25], touch voltage [26] and earth current [27], are also found with good extent of success; while analysis on harmonics [28], fault detection [29] and electromagnetic compatibility needs the traction power system simulation as an auxiliary tool to supply background data. For power engineers, results from probabilistic simulation give sufficient indications to peak demand and voltage variations. On the other hand, railway operators may need detailed simulation results when they need to investigate continuous changes on voltage and current over a specific time-span.

In addition to studies related to the power system, traction power system simulation has also come to the aid of train operation and control. When train operation is manipulated to fit particular timetables or schedules, the resulting power demand and/or energy consumption have to be checked for possible saving and/or infringement of system constraints. Power system simulation has been employed to evaluate the impacts and merits of re-starting regimes of train queues [30] and different coasting control strategies to meet run-time requirements [31] by simply providing the data on the supplied power and energy under specific train operation arrangements.

5. FURTHER CHALLENGES

Simulation always relies on accurate modelling of the functions and behaviour of the system to produce reliable results. In traction power system simulation, the models on various components of the system are quite mature. Despite continuing effort to pursue more accurate and elaborated models, such as rail track, rail impedance, motors [32-34] and even driver behaviour, the outputs from the existing simulators are of acceptable accuracy upon verification. There are always new systems or set-ups which require different modelling and Meglev is one example [35-37]. Further development on modelling often enhances the level of details in the output or targets selected investigation objectives.

On the other hand, computational demand is certainly going up with more complicated models. If it is desirable to maintain the applicability of the simulators or even to incorporate them into on-line control software in an advisory role in the future, parallel processing techniques [38] to reduce computation time and a carefully structured approach to software validation are required. Parallel processing can be applied to both hardware and software. With hardware, a number of processors can be connected in a specific configuration and the difficulty is to spread the computation evenly to the processors to achieve the maximum throughput. On the configuration of processors, there are many possible systems, based on different parameters such as control mechanism, memory configuration and number of processors. Since the matrix is a 2-D data structure, it can be easily mapped into a linear or a mesh array.

Even with a single processor, parallel processing is still possible with the aid from software. PCs are still the common adopted platforms for simulation and their popular Inter Pentium III or above processors allow parallel data processing within their structure. They include SIMD (Single Instruction Multiple Data) registers where data parallel operations can be performed simultaneously. Streaming SIMD extension has provided a powerful computation tool for performance improvement. The SSE registers are 128-bit wide and they can store floating-point values, as well as integers and characters. There are eight SSE registers in a single processor, each of which can be directly addressed using the designated names. Utilising the SSE registers in the traction power system simulation software becomes a straightforward process when suitable tools [39] are available. In the case of integers, eight 16-bit integers can be stored and processed in parallel. Similarly, parallel manipulation of four 32-bit floating-point values also fit the 128-bit registers.

With 32-bit float-point numbers representation in the traction power simulator, a maximum computational speed-up ratio of 4 is expected without any additional hardware. In a previous study [40], a speed-up ratio of around 3 is achieved with LU decomposition of matrix, depending upon the size of the matrix. The main reason for not attaining the maximum speed-up of SSE mechanism is the processing overhead on packing data into, as well as unpacking data from, the 128-bit format. The number of packing and unpacking operations is proportional to N^2, where N is the size of the matrix. Software techniques, such as loop rolling and pre-fetching, have been applied in a subsequent study [41] to improve the speed-up ratio slightly. Further works on employing assembly codes to accelerate the execution of this section of software program are now undertaken.

6 CONCLUSIONS

This paper reviews the key modelling features in traction power system simulation and highlights the difficulties with the supply systems and loads. Results attained from two approaches of simulation, deterministic and probabilistic, are presented to illustrate the diversity of output formats. A wide range of successful applications, electrical-related or otherwise, has also been introduced briefly here to demonstrate the versatility of the simulations. Extensive work on parallel processing is identified as one of the primary direction for further development on traction power system simulation, particularly when it is to be included in real-time applications.

Traction power system simulation has been a widely adopted but unsung computer-aided engineering tool for railway power engineers for the last two decades. This paper collectively summarises the research effort and experience on the existing simulators and their underlying principles. With the advances in hardware and software, newly developed traction power system simulators may evolve with fresh functionalities and features but the fundamentals on modelling and system constraints remain. Accurate, reliable and efficient simulation is still critically essential for studies and analysis of all natures at the design, operation and planning stages of electrified railway systems, which is an integrated part of railway transportation system engineering.

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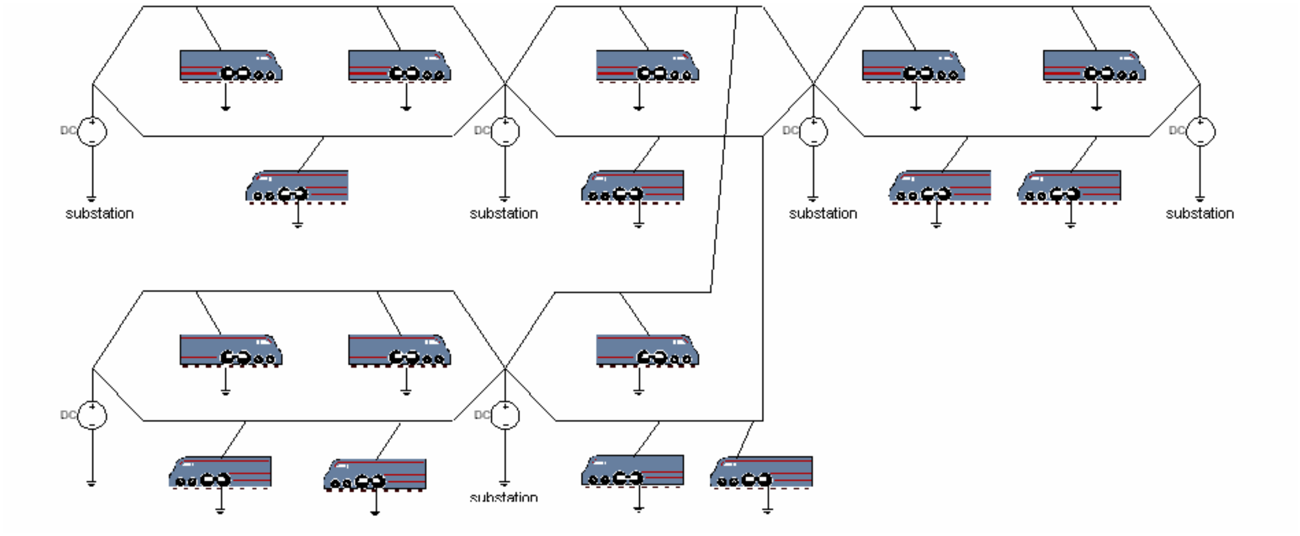

Fig. 1 Branched two-road network with DC supply

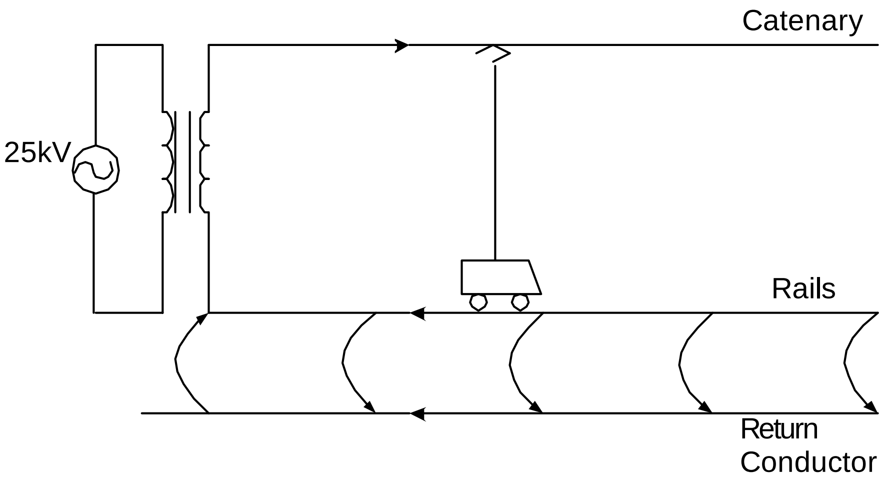

Fig. 2 Direct feeding with return conductor

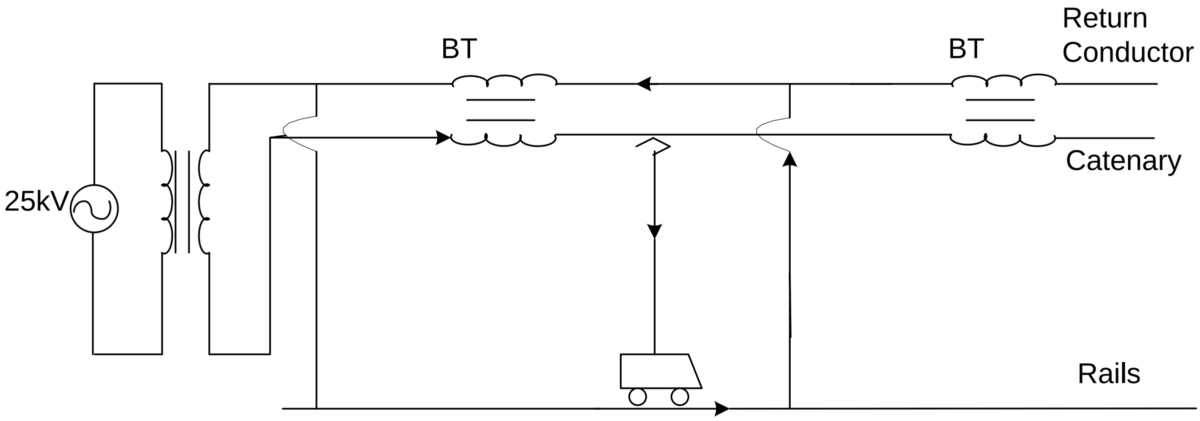

Fig. 3 BT feeding

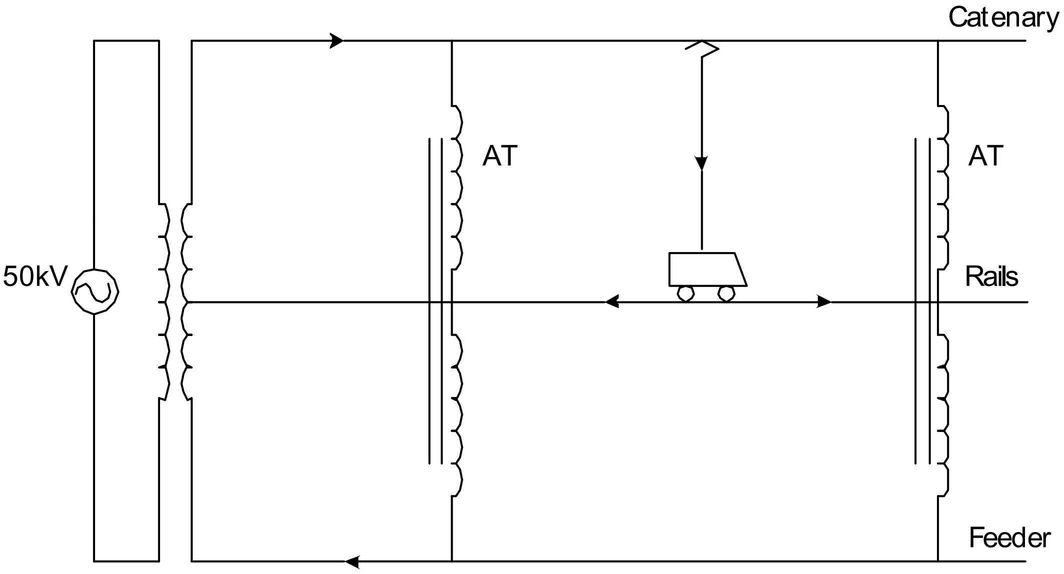

Fig. 4 AT feeding

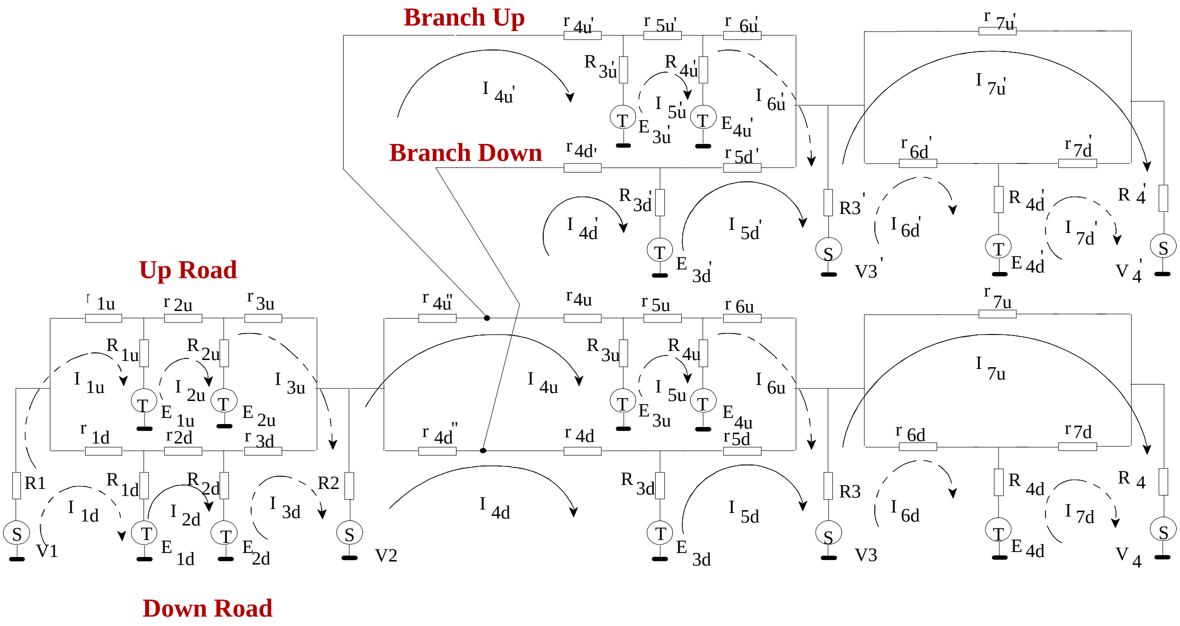

Fig. 5 The equivalent circuit of a typical power network with branches

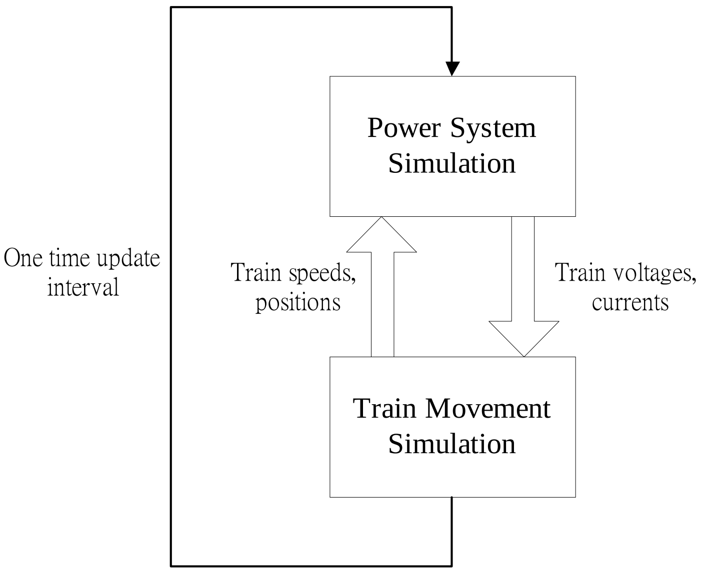

Fig. 6 Interaction between power system and train movement simulators

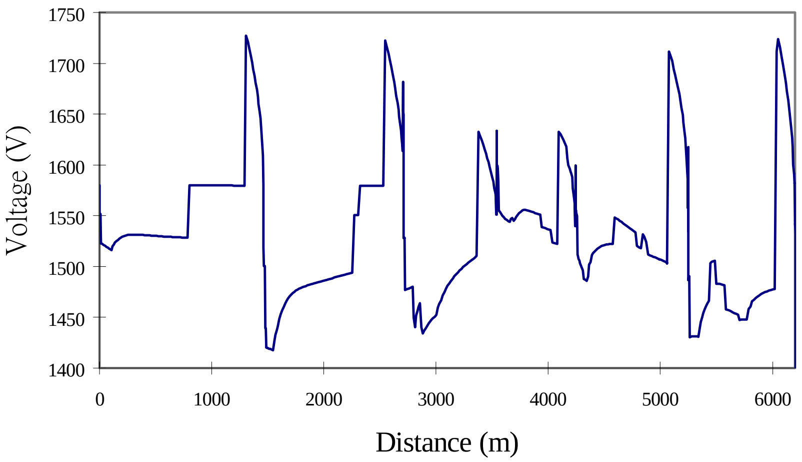

Fig. 7 Train voltage against distance

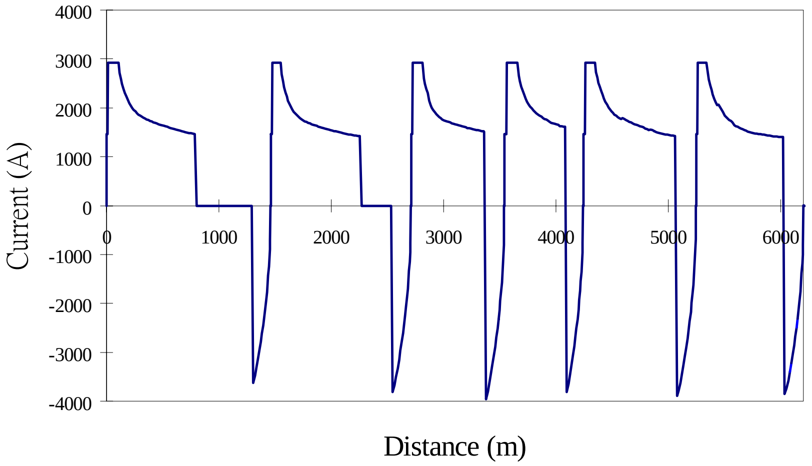

Fig. 8 Train current against distance

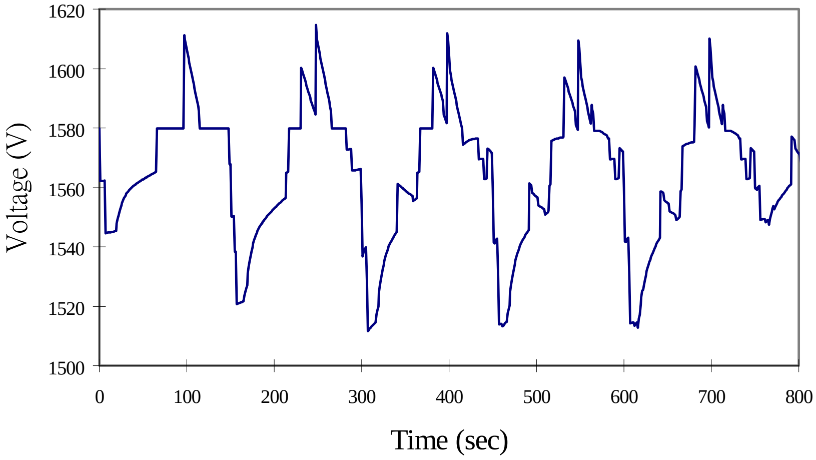

Fig. 9 Substation voltage against time

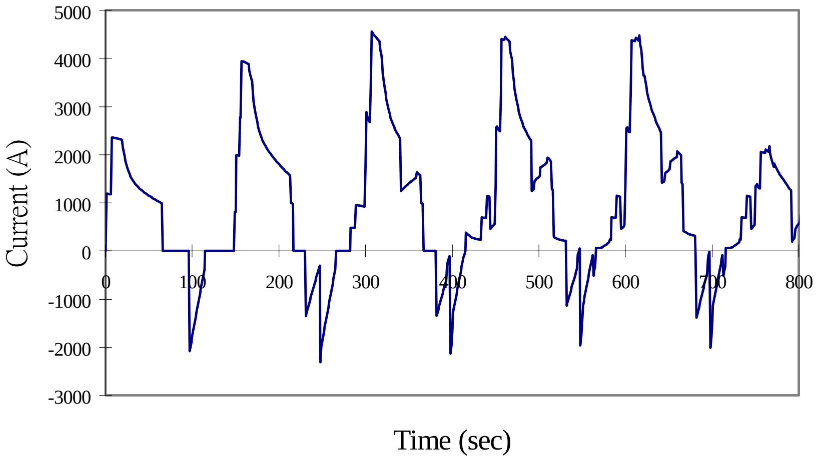

Fig. 10 Substation current against time

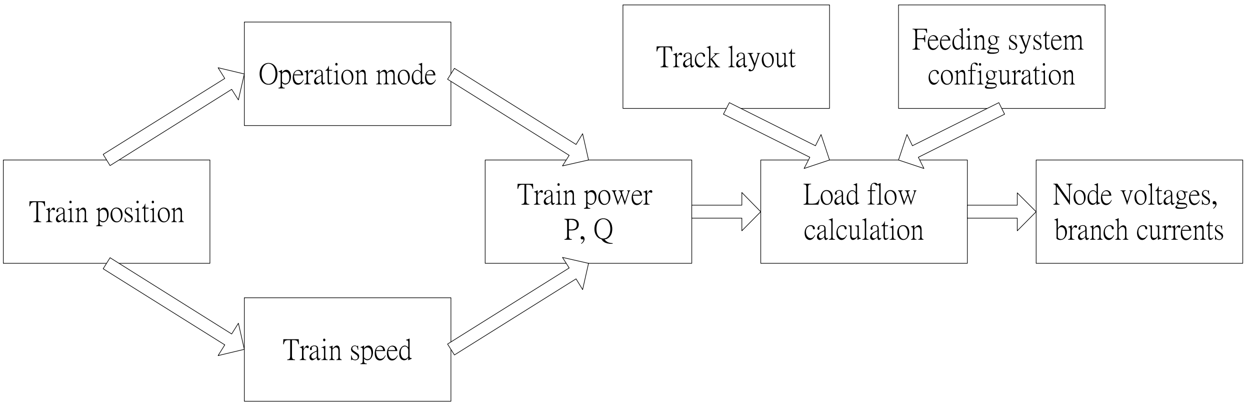

Fig. 11 Processing from a train position sample to power system solution

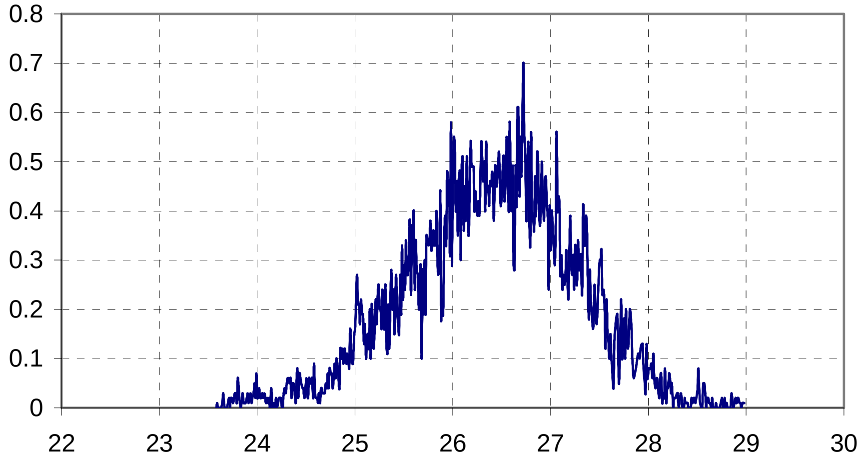

Fig. 12 Train voltage pdf

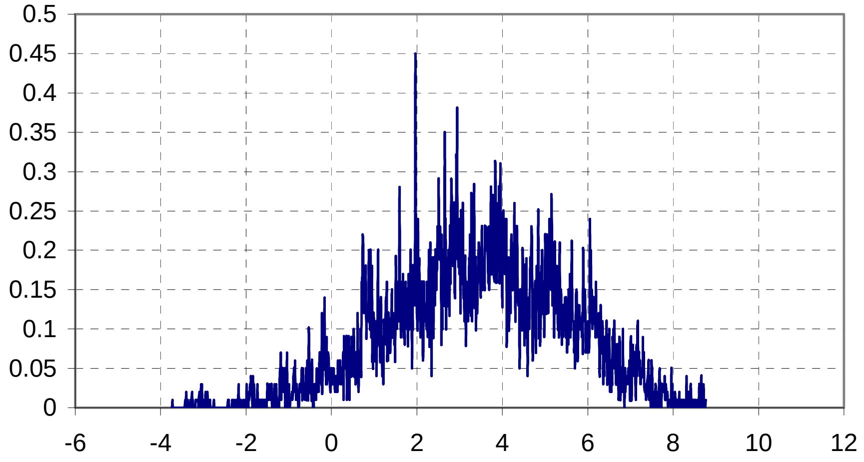

Fig. 13 Pdf of active power demand of a train

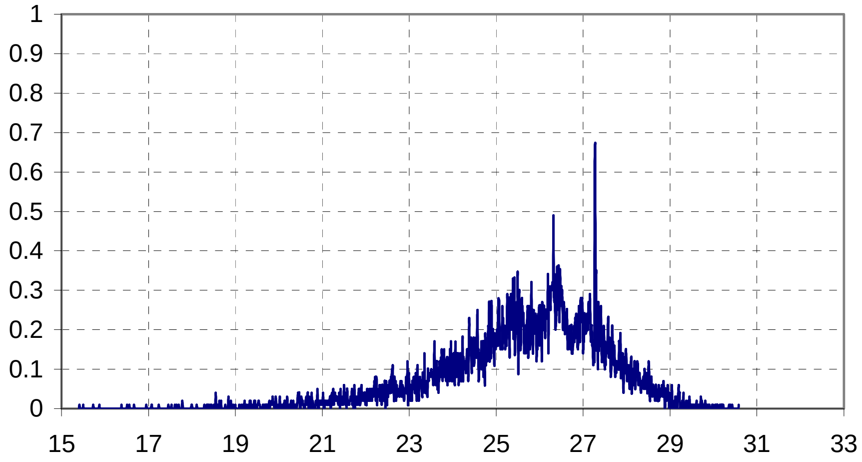

Fig. 14 Train voltage pdf of train with direct feeding

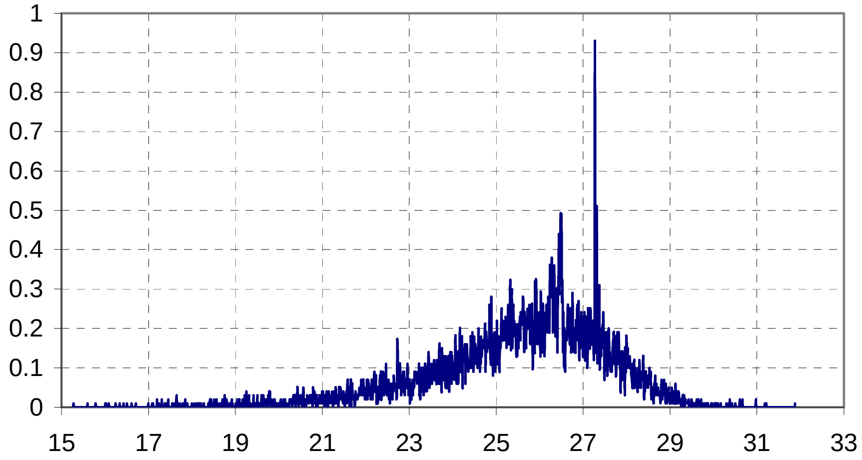

Fig. 15 Train voltage pdf with BT feeding

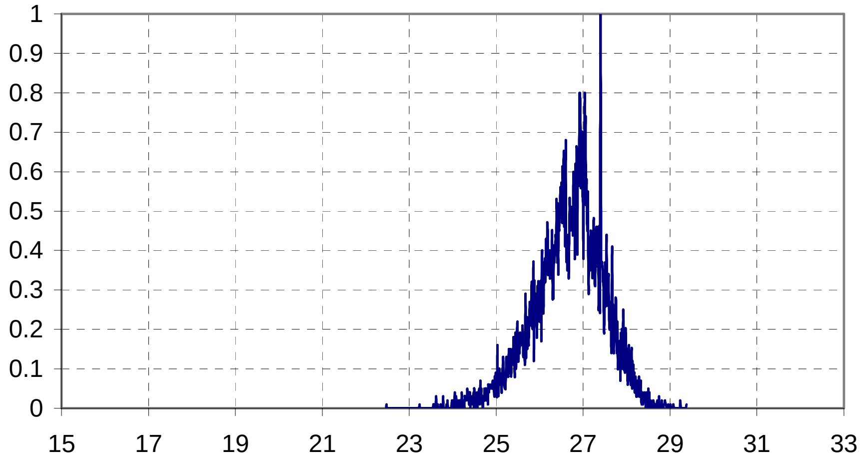

Fig. 16 Train voltage pdf with AT feeding