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Applications of Power Electronics in Railway Systems

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Abstract—Power system interface with electrified railways (ER), auxiliary power, hybrid trains, electromagnetic interface (EMI) and traction are reviewed in this paper for diesel electric trains and ERs. Auxiliary power supply is a low voltage AC/DC power supply for onboard devices with an important consideration for safety equipment. In diesel electric railways because of variable train speed, a sort of compromise is taking place between traction and auxiliary power which usually affects auxiliary equipment performance. Hybrid train’s energy storage unit can compensate this deficiency. Other challenges in railways are their compatibility with power and communication systems.

Index Terms—active filters, electrified railways, hybrid trains, electrified railway power system, power electronics.

I. INTRODUCTION

Railways are basically categorized to Electrified and Diesel-electric systems. This classification dictates a majority of their characteristics.

Auxiliary power is a low voltage AC and DC power supply for different onboard devices. The other challenge in railways is desirable performance of auxiliary power supply to keep lights, air condition etc. regardless of trains running mode and rail conditions. Considering that safety equipment is powered by an auxiliary power supply elucidates its importance. When it comes to auxiliary equipment reliability in diesel electric because of varying running mode a sort of compromise is taking place between traction and auxiliary power. This usually affects auxiliary equipment performance. Hybrid train’s energy storage unit can make up this deficiency. Other general assertion is [14] which explain china’s railway potential for new technologies.

II. TRAIN SYSTEMS

There is a general power based classification in [3]: Light rails with less than 1MW. Medium loads are commuter (3-4 MW) and high speed intercity (4-6 MW) trains. Very high speed commuters (TGV: 8-10MW) and freight trains (EU: 6-10MW, US: 18-24MW) are high demand railways. To establish a railway system its economical and technical feasibility, compatibility with other power system customers and adjacent communicational systems should be considered [3]. Light trains are designed to stop every 2 or 3 km to cover a wide urban area and they require accelerating and decelerating fast enough to be efficient. When the working field of railway is wider to cover suburban areas, commuter trains come along. They travel in longer distances and longer intervals (5 to 10 miles) between each stop and with higher speeds (125 mile/h). Their feeder voltage needs to be AC to reach high enough voltage levels of 15kV or 25 kV. If frequency of stops is reduced to achieve higher speeds and more carriage, high speed intercity trains will be defined. An identical ex. for high speed train is TGV which has a single phase 25kV; 50Hz on its catenary TGV can travel up to 330 miles/h. the power supply of TGV is handled by French national grid on voltage levels of 275 kV or 400 kV to increase reliability and power quality. There are other high speed railways (HSR) like ICE in Germany or HSR 350X and KTX in Korea [5] Sinkansen and Maglev in Japan. For general information about worldwide high speed trains are described in [17].

However very high power traction motors are applied in freight trains especially those are running in US. They run in a low speed high power manner. Because of this high power and lower priority of freight in comparison to passenger carrying railways, freight electrification has more power quality problems and less economical justification.

III. POWER QUALITY

One of main problems regarding to electrified rail ways is power quality shortage that can reduce other customers’ usage efficiency below standards. Railway produced power disturbances which can be classified as below:

A. Power Unbalance

Since electrified trains are single phase loads inherently, connection of these time varying (as much as they are high speed) unbalance (as much as they are high power) loads to three phase power system will lead to huge power unbalance. This problem has been facing different solutions. Firstly some
countries devoted a specific power system to their ERs and made other customers isolated from power quality disturbances produced by railway. The other solution is to use DC transmission systems for trains. This strategy is working and different standard and a few not standard DC voltage levels are used to supply railway system. In this approach railway is connected to a main power system through an ACDC rectifier and all of the power turbulences are cut off at a point of common coupling by this high voltage rectifier. The other solution was to design railway train to work as AC load but not necessarily with standard frequency of 50/60 Hz. There are different voltage levels for this type of railway power feeding.

The solutions before power electronics viability for this level of voltage were limited to a few balancing transformations in AC feeders namely: V transformer, Scott transformer and Le Blanc transformer all of them well compatible with simple single phase transformation in capability of unbalance reduction. (Fig 1 from [80])

![Fig 1: Common traction system to grid configurations](image)

Also to keep unbalance system within standard levels a strong network (high short circuit duty) should be used at the voltages of 220kV, 115kV or 69kV at least.

### B. Harmonic distortion

There are speed drives, power conversion equipment or frequency converters that inject harmonic in to railways suppling power system. These harmonics can disturb other power systems or lead to high frequency electromagnetic fields incompatible with close equipment as well as train signalling system. There are some classic solutions for harmonic distortion reduction like third sequence harmonic eliminator transformers. An active power filter is a modern solution for these problems such as unbalance, harmonic distortion and low power factor problems.

### C. Flicker

As the train passes between two adjacent substations voltage sag may happen and affect other customers electrical light performance so called flicker. There are some structural solutions regarding to all of these challenges which are used in different countries. In Germany and Sweden low frequency systems are used which are low frequency power system in Germany and frequency conversion in Sweden. However in England, France, USA and Africa higher voltages has reduced the problem in different manners which are connecting railway supply system to main network in a high voltage point of common coupling or designing railway system to work under a higher catenary voltage. All of abovementioned methods are relying on a strong power system at the PCC to keep unbalance under 2% and harmonic distortion within standard limits as well.

### IV. ACTIVE POWER FILTERS

Considering power electronics facilities new frontiers opened to power quality compensation solutions. Load unbalance can be attenuated by making controlled power transmission paths between two or three single phases owing to power electronic switching circuits.

In [16] 25 kV feeder characteristics are presented and reasons for power quality problems in railway systems are mentioned, followed by brief description of methods for compensating these shortage. Namely:

1. Reducing the distance between 25kV supply substations.
2. A higher fault level at each 25 kV supply station.
3. Using static VAR compensator as voltage support at each supply point.
4. More switching stations between each two adjacent substations to limit faults.
5. Series capacitors either in substations or overhead wiring.
6. Shunt connected capacitors either as circuit-breaker capacitors or reactive power compensator.
7. Transformer type series regulators in the overhead line.
8. On-load tap changing transformers installed for each substation.
9. Paralleling feeders to share load between them and alleviate unbalance.
10. Engineering the geometric configuration of feeders to reduce its series impedances.
11. Single phase transition to distant stations at a higher voltage to decrease voltage loss.
12. Paralleling of adjacent substations via the overhead line.
13. Installing switching capacitors on board.
14. Twining contact overhead lines to reduce inductance and resistance and increase the line’s current capacity.
15. Unbalanced autotransformer voltage.
16. Storage batteries connected by inverters to collect extra power and support overhead line voltage.

#### A. Active filters structural characteristics

In [26], [27] and [65] power electronic compensators are designed, simulated and experimented to control voltage form factor on 25 kV ERs. The presented active power filter in [26] and the hybrid (passive and active filters) multi level ones
presented in [65] and [27] are shunt connected to solve both harmonic distortion of 3rd, 5th and 7th harmonics and low power factor. The shunt compensator is installed at the end of overhead line and works regarding to the voltage which senses at its connection point. In [67] an algorithm to achieve high performance selective harmonic extraction is revised. In [68] same active filter as [65] is deal as impedance connected to end of feeder line. The paper is optimizing this impedance to find the most effective control strategy for proposed active filter to achieve acceptable voltage pantograph along the whole line. In [64] another shunt connected active power compensator is presented that suppose to compensate unbalance created by railway application on power system in addition to reactive power required by traction motor. The method is upgrading a traditional Scott transformer with a bidirectional inverter that can balance two output phases of Scott transformer by transmitting a fraction of overloaded phase to under loaded one. By side the inverter compensates harmonics. [33] has realized same but more advanced strategy for Shinkansen high speed railway (HSR). (Fig 2 from [33])

In [66] a different compensating method is introduced which adds a medium voltage level between main supply and railway lines. The compensator which is a two phase inverter is connected to this medium voltage line and senses and then regulates this voltage. (Fig 3 from [66])

**B. Active filter equipped power systems analysis**

In [51] a power system simulation has been directed to extract unbalance vulnerability of a test network. According to [51] voltage and current unbalance are related to train load and motion conditions and power supply configuration. Classic methods of unbalance alleviation which generally are 3 phase to 2 phase transformers are considered in this unbalance effect study (3 phase to 4 phase transformation for railway application is proposed in [75]). To compare different railway load distribution effect four experiments with varying loads and different arrangement has been prepared.

[48] specifically focuses on active filter for tram. Unlike above mentioned active filters this one acts as an input or series filter. In [37] the mathematical technique of Diakoptics is applied for railway system solutions. Diakoptics is to tear a given system into a number of independent, then joining the solutions of separated parts together for the solution for complete problem. It is a good idea for railway power system with indispensable characteristic of changing loads and more identical: changing structure of under study railway system by its train’s movement. In [69] harmonic analysis for Korean railway system has been implemented. To direct this study an eight-port model for considered railway is defined and presented. In addition, to certify proposed model simulations based on the model is compared with measurement in. Further more amplification of harmonic by resonance in railway electrification system is studied. In [31] a mathematical approach to extract general control strategy for advanced 25kV-50Hz ERs has been performed. The objective of nonlinear control is to attain current and voltage balance in power system regardless of uncertainties and nonlinearities. In [79] a purely structural approach calculates the optimal positioning of RC-banks to reduce harmonic distortion in a given railway network. Then Optimization is focused on R and C amounts to alleviate harmonic amplification. In [78] the case of Taipei MRT DC system is studied, focusing on harmonic quantity and quality. In [78] practical measurement method
which is used in this study is explained and measurements results are presented and compared with mathematical predictions. Then parameters that can not be easily considered in mathematical harmonic analyse methods are named and the difference they make is shown in measurement results. In [49] Olympic electric train is studied in the power quality point of view. Chargeable batteries are used to improve power quality in case study system. In [86] and [92] probabilistic methods for load flow in ER suppling power systems is suggested. They purpose to layout Probability density functions of voltage or power flow in certain point of the power system which indicates the ranges of variations of these parameters. In [80] traction unbalance problem is discussed and some methodologies to analyse are presented. Then a new method is offered which is based on sensing and compensating the negative sequence of three phase power supply. The point about this idea is that multiple sources of unbalance do not interact because their effect on negative sequence is additive and can be deal separately.

In [70] three level PWM inverter which is used for the HSR traction drive is studied. The purpose is to analyses its harmonic current characteristics in steady state mode. A comparison between a three level converter harmonics with a pair of interfaced two level converters is presented and resulted to their equality in this point of view.

In [71] a model of an auto transformer fed AC HSR is presented. Voltage pantograph in HSR is more problematic because of fast change of load and structure by train’s movement. [71] has utilised its proposed model to introduce a generalized, multi rout, and efficient method to solve complicated system of working HSR. In [72] a mathematical work is done to estimate voltage unbalance due to HSR power demands. Different main power supply and feeder connections are considered and there potential to reduce unbalance is compared. [90] has suggested a rigorous way to evaluate voltage unbalance produced by single phase HSR application on power system. This new method’s results are compared with traditionally formulas for unbalance estimation. In [90] the case of Taiwan HSR is studied. Another study concerning about unbalance estimation is presented in [91], which uses dynamic load estimation (DLE) to predict railway produced unbalance. In this way an algorithm is illustrated which is used to estimate dynamic load of Taiwan HSR and then foresee unbalance affect of this changing load. In [93] the regarding power system (Taipower) which -due to geographical situations- is a longitudinal power system is studied to extract impact of HSR on such a power system.

V. SIGNALING EARTHING AND EMI ISSUES

The other challenge issue in electrical and diesel electric railways is EMI. In other words railway engineers need to make sure that their system is compatible with communication systems either railway’s signalling system or other in close proximity RF communicational systems. In addition rails may be use as signalling conductors. Nevertheless rails may act as a part of return path for power current. This multi application makes a compatibility challenge which has a considerable number of related papers. EMI is strongly related to earthing methods because currents passing through earth connections can be directed by high frequency harmonics and produce high frequency electromagnetic fields.

In [60] electromagnetic compatibility (EMC) of an auxiliary power electronic converter for London under ground trains is studied and results are presented. It has classified EMC to these subtitles:

1) Signalling interface
2) Magnetic fields
3) Telephone interface
4) Radiated RF (radio frequency) emissions
5) RFI (radio frequency interface) Immunity

The source of EMI is power converters on vehicle board. This research tries quantizing EMI and EMC in proposed underground railway. In [36] earthing and bounding of ERs are studied. Different structures of 25kV and 2x25kV AC railway feeders are presented and concept of earthing is discussed regarding to them. Then DC railway feeders are premeditated and their practical earthing and bonding strategies are presented. At the end earthing in depots is addressed, which is most the challenging problem in earthing engineering. Because safety, corrosion, operational and technical requirements have to be satisfied by earthing in this area.

[21] is about signalling and inter locking in railways which are concerned about two traffic control issues. Firstly to keep safe distance between two trains running in same rail, secondly traffic controlling in intersections and junctions. The safe distance depends on trains’ dynamic state and rails situation, so it should be sensed correctly. [22] is explains about train detection in details. Related communication and supervision is discussed as well. [23] is focused on EMC in both approaches of disturbance source and equipments vulnerability. Some potential problems caused by EMC are mentioned in [23]:

1) Interference to safety signalling systems from power electronic traction vehicles.
2) Interference between AC and DC traction electrification railway systems.
3) Safety hazard due to electrical voltage induction on metal fences near the track.

[23] Has categorized EMI in railways to internal, outgoing and incoming.

It is followed by some general strategies to alleviate EMI produced in traction system [24]:

1) Frequency departure of traction power and train’s signalling system.
2) Appropriate cable screening, termination and positioning for inductive interference reduction.
3) Suppression of arcs drawn by traction power current collection systems to reduce RF interference.

[24] Continues accurate mathematical calculation to attain EMI vulnerabilities of railway system related to traction system. There are more general and concentrated papers in
signalling ex. [100] is around British Railway’s history in signalling technologies. [101] is an early survey on signalling systems, Which has theorized signalling and listed common purposes of signalling ex. speed increasing, reduction of distance between trains and so increasing rail capacity. [102] has suggested formal mathematical methods to specify and design railway signalling schemes.

When the case is mass transit railway systems, signalling strategy can contribute in concepts of power and energy management. For ex. starting time of multiple running trains which are supplied by same power network has considerable effects on peak power demand. Regarding to mass transit railway systems [103] has suggested generic algorithm to optimize traffic.

[104] has explained a heavy traffic light train railway from the signalling point of view. The main obligation is to arrange signalling in a way that trains can keep moving and interrupts be eliminated. The innovation suggested in this paper is to use separated communication system to locate moving trains by data transfer between train and a parallel installed communication system. Traditionally partitioned rails were used to detect moving trains’ positions, as accurate as shortness of each rail partition. To compare abovementioned train detection systems with recently proposed systems, [105] can be mentioned which considers application of GPS for signalling and train position detection. At last [106] and [87] are explaining technical aspects about application of satellite in railway signalling and navigation. To have a broader approach to railway system compatibility concept [52] is worthy to be reviewed. It covers all of probable compatibility problems including EMI.

VI. INPUT VOLTAGE SOURCE

As mentioned in train systems classification there are some voltage sources which are used based on trains exact application (Appendix I). Concentrating on input voltage, source railways can be categorized as below:

A. DC

The main advantage of DC traction system is simplicity in control. DC voltage supplied ERs can be split in two approaches. Firstly voltage level of the feeders and secondly the measure which is used to feed the train. Standard DC voltage levels under load over the world are 600 VDC, 750 VDC, 1500 VDC, 3000VDC. There are some non-standard voltage levels as well. (Appendix)

In another approach DC ERs can be classified in which main DC power supply is connected to trains. Overhead line system and Conductor rail system is main sub categories which can be manufactured in different schemes. Although the feeder structure for voltage level of 3000VDC and more is limited to overhead lines. DC voltage supplied railway systems are recommendable for low power applications. Higher DC voltages for higher power railway application are not practical because of insulation and clearance restrictions. The power system interface of DC feeder systems is limited to some harmonics injected to power system at substations that can be attenuated by appropriate filters. The other problem with DC railway supply system is ground return current that may be cause of corrosion.

B. AC

standard AC voltage supply for ERs are 25 kV, 50 Hz - which suppose to dominate Europe railways as a regional standard to unify European railway system [8] [7] [28] [6] [4]- or 25 kV, 60 Hz for countries with 60 Hz power system ex. Japan, US and 15kV, 16.7Hz –in Germany, Austria and Scandinavia- and 50kV 50/60 Hz or 2x25kV [94], 50/60 Hz using auto transformers –for very high power applications- all installed as overhead single phase lines. Due to less insulation restriction with higher frequency, much higher voltage level is feasible in AC power transmission to trains, leading to remarkable reduction in power lose.

The other subcategory of AC supplied railways is those which are working with a lesser frequency than main network’s. Low frequencies systems like 25kV/12.5kV and 25Hz, 16.5kV and 16.7Hz, and 25kV/15kV and 15Hz have the advantage of lower inductive lose in comparison with standard frequencies of 60/50Hz [29].

Distance between substations and power of each substation depending on trains load, speed and catenary characteristics varies among 20 to 80 miles. Basically the higher feeder voltage the longer distance between substations is allowed. multi voltage traction systems are designed to remove the need of locomotive change when voltage level changes [61].

C. Diesel

The much more different category of trains those are using electric motors for traction is diesel electric trains that use diesel engine as primary power supply and then rotating an electrical machine that produces electrical power for electrical traction motor. This sort of train has no counterpart when it comes to long enough distances application, when electrification is not economic due to its costly infrastructure requirements. The main problem of diesel electric railways is primary source of energy that is , unlike ERs, limited to some fossil fuels usable on exhaustion engine on board, so efficiency is an important aspect about diesel electric trains because contrasting ERs there is not much opportunity for energy regeneration in cases of braking or down hill running. A majority of studies in this way are trying to apply an energy storage equipment to have some temporary places for regenerative braking and more efficient and less polluting performance of diesel electric train.

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of current interest.

VII. ENERGY EFFICIENCY AND POLLUTION REDUCTION

In electrified as well as diesel electric rail energy efficiency and pollution reduction are strongly coupled and important issues. There are some methods to save energy in railway systems which are addressed in [25] and [62]:
1) Reduction of braking losses by optimized driving.
2) Optimization of speed profile
3) Avoiding rout conflicts to keep optimal speed.
4) Tuning time tables in ER to fit nearby trains to exchange energy.
5) Optimization of power chain.
6) Devising smarter and more efficient auxiliary equipment.
7) Automatic railways, which allows optimization of transportation as a whole.
8) Vehicle structure optimization.
9) Energy recovery and storage:
   The last one is studied more. When it is about ERs, depending on other trains’ dynamic situations a certain decelerating (down-hill running) train’s kinetic energy can be transferred to another accelerating (up-hill running) one. This approach is deeply limited to railway supply power system structure and trains position, so can not increase efficiency more than a few percents. However this method faces more problems in DC supplied lines due to incapable rectifiers. The other general lack of this approach is energy loss in feeder lines when it is transmitted between trains. This deficiency increases by voltage level of feeder’s reduction. The other approach is based on energy storage modules. Some papers are reviewed to assess this concept:

A. Hybrid trains

In [1] a diesel traction system has been upgraded with storage battery. Battery is managed to store brake energy and reuse it for acceleration periods and to stabilize the auxiliary power converter DC link (Fig 4 from [1]). In other words energy storage module decouples power produced by diesel engine and the power consumed by traction motor and auxiliary power, by storing and reusing energy. In addition, mentioned decoupling between diesel engine and electric motor allows the engine speed to be controlled irrespective of the train speed; instead it can be set to increase fuel consumption efficiency by working on an optimum point. [96] is focusing on battery application on hybrid trains from various angles: tractive effort, power, economics, and etc. In [45] Hitachi prototype of a hybrid train manufactured by employing a 10 kWh battery as energy storage device is introduced. In conclusion future adventures of purely battery powered trains or trains which their diesel engine is replaced by fuel cell or other environmental friendly energies are named. To mention realized examples, [97] can be named which explains about a photovoltaic energy supported funicular installed in Leghorn, Italy. Or [95] which is referencing to an experimentally realized rail vehicle that employs SuperCaps as lone power source.

Fig. 4 a typical configuration of hybrid vehicle system

In [2] another diesel electric locomotive efficiency has improved by means of a SuperCap. Same structure and two approaches in [1] are considered in [2], except battery is replaced by SuperCap. Ideally, if there be sufficient energy storage, the suggested structure can remarkably reduce engine rating. SuperCaps have their limitations and their situation along working should be monitored to keep them within healthy condition [98]. [30] has mentioned some other advantage of energy storage capability in railway systems. Such as:

- Substations can be established farer
- More trains can move on a given feeder system.
- Running in limited areas of electrical railway without catenary. Running with switched off diesel engine in highly polluted areas for diesel.
- Reducing travelling time or CO2 emission.

A comparison between battery and supper capacitor usage is presented as well. In addition [30] has considered SuperCap’s potential as a booster of power in acceleration or up hill running modes. The main problem with braking recuperation is non-ideal energy storage units which mean rather low energy capacity for Super Capacitor (SuperCap) or not enough power rating for batteries. Here the idea of combining batteries and SuperCaps to cover their shortages comes along. In [32] SuperCaps and batteries are applied to achieve mentioned advantages with an enhanced performance in addition to smoother and more efficient application of both battery and SuperCap. High power capacity of SuperCap is used to release battery from peak power. This has economical promote of increasing costly battery’s life time. On the other hand high energy density batteries are used and need for high energy storage in SuperCaps is removed, which means another cost reduction in construction stage. In [54] a state of art hybrid train is presented in which battery or flywheel is implemented to cooperate with a fuel cell as prime energy source. [54] concludes that the most suitable train for regenerative braking are long distance intercity commuters. And the least likely to profit hybrid traction are high speed and heavy cargo operations. In part one; it is focused on middle distance transport with diesel base hybrid locomotives. In part two; fuel cell –instead of diesel- application in passenger transport is
under study. [59] focuses on dynamic brake energy recuperation on North American freight locomotives. It suggests hybridisation for a route that has two characteristics: it contains 25 miles long down grade and it has a heavy traffic of about 80 traversing trains a day. [73] and [99] has approached Superconducting Magnetic Energy Storage (SMES) and battery energy storage combination as a load levelling device. Simultaneous application of SMES and battery is optimized to increase life cycle of both. Another optimization in [77] is undertaken to minimize volume of storage unit. In [99] SMES is connected to feeders unlike [73] and [77]. (Fig 5 from [77])

![SMES application in electrified railway](image)

**Fig 5: SMES application in electrified railway**

VIII. POWER SYSTEM

A. Traction

A part of traction system related papers are about traction motors. Other important part is power converter which is strongly related to power electronic availabilities [38]. [18] and [19] are two first parts of R.J. Hill’s tutorial papers which are about DC and AC machines as traction motors respectively. In [18] General mechanical equations describing train mass’s behaviour is presented at first. Then the drive characteristics are presented. Different modes of operation for DC traction motor –motoring, resistive braking and regenerative braking- are discussed. In [19] Practical advantages of induction motor have made it attractive for harsh application of railways. Drives applied for AC traction motors are presented. In [20] Different categories of DC and AC motor motivated trains in British railways are compared in different views of working environment, power/weight ratio, motor make up, mounting methods, cooling problems, etc. In [42] a sensor less control system for an induction motor for railway traction system is presented. Rotor speed in this system is estimated by electrical measured quantities. Elimination of rheostatic steps for speeding and braking has improved movement smoothness and thereby passenger comfort. In [39] some power electronic circuits for traction application either in electrified or in diesel electric systems are presented. Fundamental information of this paper can be useful. Other reviewed papers which utilize early power electronic equipment are [40] and [57]. [15] is explaining a diesel electric train serving in Indonesia.

[41] Has improved traction system to act as reactive power compensator. To achieve optimal result a central control system dictates each trains reactive power to minimize power loss along the line. [46] is a general paper which covers power electronics enhancements which are interesting for traction application. It has focused on a comparison between IGBT and IGCT at last. [43] introduces new generation of IGBT switches tailored for traction. The presented IGBTs are employed in an experimental train’s traction system. [44] has concentrated on AC/DC and DC/AC converters in HSR traction application. It has suggested a modular topology to supply multiple induction motors with multi level modulation satisfactorily. For auxiliary power an extra transformer winding is devoted. [47] introducing a tram traction system which aims to reduce the energy consumptions in addition to increased safeness and travellers comfort. The tram is running in Croatia and results are experimental. In [50] a vector controlled tram traction system is presented and manipulated. Regenerative braking is considered for [47] and [50]. [63] is a vector control induction motor study realized for traction application. [75] presents a control system for motor suppling power electronic circuit, which suppose to feed traction motor without a regulated DC link. [84] analyses traction system as a whole including inverter, rectifier, and contactor and DC traction motor.

B. Auxiliary systems

[9] is “IEEE standard for passenger train auxiliary power systems interface”, which describes auxiliary power requirements as a standard. [11] and [53] are technical papers which list considerations required in auxiliary power design to satisfy railway operator’s requirements. In [10] auxiliary power configuration in whole train combined of motor cars and passenger cars is explained. In [12] a novel power control method suitable for auxiliary power supply system is presented, which targets to achieve high reliability by redundancy. It keeps power factor of auxiliary converters high. To avoid circulating currents between Auxiliary power converters, one of them is controlling its power factor and others obey it. In [13] the new topology of full-bridge three-phase isolated DC/DC converter is suggested. The input DC voltage is inverted to three-phase AC and then is rectified by a full-bridge rectifier. A new type of multi level DC/DC converter designed for auxiliary power supply application is proposed in [82]. The proposed converter is based on half bridge converter. [55] suggests some ideas to have more effective and efficient auxiliary equipments. Like fibre optic application in rolling stock (realized in [35] as well), smart battery and charger control methods, etc.

[58] Introduces a specific prototype of auxiliary power supply system, which has applied IGBT as high power
switches. In [81] an adaptive inverse model controller is devised to compensate non-linearity and imperfections of components. Switching strategy is a modified PWM to adapt duty cycle with nonlinear and non-ideal system.

In [83] a two-switch high frequency flyback converter is developed to achieve ZVS. A few modules of proposed converter can be paralleled for higher power. The input voltage of dc/dc converter in [83] is obtained from a fuel cell. The characteristic of this circuit is the application of energy from leakage inductance of transformer. Due to the fact that auxiliary power despite of input voltage fluctuation has to provide a regulated voltage at output, some papers around this purpose reviewed:

In [85] a phase modulated full-bridge converter is improved to decrease output voltage harmonics and enhance it to show more robustness against input voltage fluctuation. In [86] a ZVS multi level resonant converter is proposed as well as [85] phase shift modulation is utilized. For ZVS, leakage inductance of transformer is brought into play. In [88] a novel AC three phase input DC output converter is introduced. The previous circuit that the new one is based on is a three parallel full bridge rectifiers followed by buck-boost converters, which proposed paper has merged rectifiers together and uses a single buck boost converter. [89] has presented a new scheme for switching which decouples gate switching voltages from input voltage, and then it is a desirable configuration for situations with varying input voltage.

IX. CONCLUSION

There are different power systems for energy distribution in ERs and different problems to be solved in railway systems. They are namely, power balance and quality, EMC, and satisfactory auxiliary power. Active filters and more robust and flexible systems are general solutions to power system problems. More accurately designed power electronics devices are the solution for EMI problem. These solutions briefly but widely are explained here.

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