International Journal of Electrical and Electronic Engineering & Telecommunications

ISSN 2319 – 2518 www.ijeetc.com
Special Issue, Vol. 1, No. 1, March 2015
National Level Technical Conference P&E- BiDD-2015

Research Paper

A MODIFICATION OF RAILWAY ELECTRIFICATION SYSTEM USING CONVERTOR

G Gayathri[1]*, K Sindhu Bharathi[1] and C Kamal[1]

*Corresponding Author: G Gayathri, ✉ gayathri94.ganesh@gmail.com

This paper proposes a new railway electrification system in which the basic building block is using convertors. In the proposed system the architecture of electrification system is done using VSC (Voltage Source Convertor) and SEPIC (Single Ended Primary Inductance Coil Convertor). The VSC-based unified scheme will substantially facilitate the connectivity among otherwise heterogeneous railway systems, while the integration of distributed generation and storage is achieved in a straightforward fashion. The need for a supervisory control system, and its role in coordinating is done using local VSC controllers, so that the resulting power flows are optimized while the catenary voltage is kept within limits, are discussed. SEPIC converter is used to increase or decrease the voltage. The SEPIC converter allows a range of dc voltage to be adjusted to maintain a constant voltage output. The proposed railway electrification paradigm is compared with existing MVDC (Medium Voltage DC)architecture compared with the standard 25-kV, ac electrification system by means of real case study.

Keywords: Terms-VSC convertors, SEPIC convertors, MVDC converter

INTRODUCTION

The current ac electrification infrastructure has to comply with a number of regulatory standards which determine the design characteristics regarding apparent power and location of traction and autotransformer substation Voltage limits. Standards dictate the catenary voltage range depending on the voltage level. For 25-kV ac electrification systems the voltage may vary between 1.1 and 0.76 p.u. This wide voltage range is one of the main characteristics of railway electrification systems, composed of segmented radial networks which have to withstand N-1 and N-2 contingencies (loss of one and two transformers of traction substations).

- Maximum current of cables and wires is dictated by manufacturers. As for transformers, it has to be considered that the load cycle is quite variable. Moreover,

[1] UG Scholar, Jeppiaar Institute of Technology.

N-1 and N-2 contingencies have to be taken into account.

- Voltage imbalance. The impact of the railway system on the bulk power system has to be considered in terms of voltage imbalance as the rolling stock is a single-phase load. The negative sequence has to be limited.

ELECTRIC traction offers many advantages over diesel-based systems generating power on board (fast acceleration, better performance on steep gradients, possibility of regenerative braking, environmentally more friendly, etc.), which surely explain its sustained growth, both in developed and emerging countries . Currently, two main categories of railway electrification systems coexist depending on the power needs:

- DC systems, with voltages ranging from 600 V to 3 kV, which are adopted mainly for trams, suburb trains and medium distances. Light rail, metro and inter-urban services may use both aerial catenaries or third rail, with voltages ranging from 600 to 1500 V. These dc systems are adequate for rolling stocks with low power demand (less than 5 MW). Higher powers require catenary voltages to be increased up to 3 kV. As a rule of thumb, 3-kV catenaries are limited to train speeds lower than 250 km/h.

- AC systems, with voltages ranging from 15 to 25 kV (16.7 or 50-60 Hz), usually found in long distances or routes with heavy traffic. Owing mainly to historical reasons, the number of ac electrification systems is really high. In fact, this electrification system has become a standard in high-speed corridors worldwide. The fact that single-phase ac is not the most ideal railway electrification system, and that dc-based systems would bring several advantages was early recognized in . However, the limitations of thyristor-based technology in the nineties imposed major impediments to this idea. Nowadays, IGBT-based technology is mature enough to allow large off-shore wind farms to be connected to the ac grid through a multi-terminal medium-voltage dc (MVDC) network]. Multi-terminal dc networks are also promising candidates for on-board electrical systems of ships and aircrafts, oil-drilling platforms and EV charging stations. One of the best exponents of this modern technology is the 2000 MW, 320 kV dc link currently being commissioned between Spain and France. From the technical point of view, perhaps the main pending challenge in the multi-terminal case refers to the lack of a suitable dc Circuit Breaker (CB), capable of disconnecting part of the dc grid in case of fault. But switchgear manufacturers are quickly progressing in this regard. Apart from, to the best of our knowledge the only reference where the idea of dc railway electrification was seriously pursued, an alternative solution has been recently proposed.

In this hybrid scheme locomotives are still fed from an ac catenary, like in existing systems, but the service ac line running along the railway is replaced by a multi-terminal MVDC system. This paper further elaborates on the preliminary ideas presented in by proposing a new paradigm for railway electrification entirely built around a MVDC system, which may involve different interconnected subsystems with voltage levels determined by the transportation requirements (freight transport, high-speed trains, commuters, etc.). The dc system is fed from the bulk ac power system by means of Voltage Source Converters (VSCs) based on self-commutated power electronic devices (IGBTs or IGCTs). In this fashion, the railway infrastructure truly becomes a multi-terminal MVDC super grid, the backbone of which is a geographically distributed dc bus feeding a number of mobile loads. This new arrangement brings out a number of benefits ranging from simpler rolling stock layouts, reduced investment on rail infrastructure, higher reliability and modularity, more friendly integration in the ac grid and new business opportunities for the railway system operator. The proposed paradigm maintains the current dc electrification infrastructure (1.5 and 3 kV), the main theme being a shift from current ac systems, like those used in high-speed corridors, to dc systems. For this reason, considering the space limitations, this paper is restricted to highlighting the main benefits that the resulting MVDC system may bring with respect to the traditional ac electrification scheme, specially regarding high-speed transportation. Other related issues, such as the possibility of simplifying and hence enhancing the integration of distributed renewables located nearby and along the railway, cannot be addressed in detail within the scope of a single paper. The paper is organized as follows. First, the current ac railway electrification system is analyzed, including traction substations, catenary and cable infrastructure, rolling stock and design considerations applied to these systems. Next, the proposed MVDC railway system is described, including all of the aforementioned issues. Finally, a case study is developed aimed at comparing both design concepts in terms of infrastructure requirements and electrical performance.

Design Details

Unlike existing ac and dc railway systems, composed of several (electrically incompatible) disconnected subsystems, each one primarily designed to serve a specific class of trains, the proposed paradigm is based on the unified multiterminal MVDC system schematically shown in. The backbone of the new railway system is a single dc catenary running uninterruptedly across the set of cities interconnected by one or several long-distance train lines. The rated voltage of this trunk network should lie between 15 and 25 kV, considering the power flows it will have to withstand. This single catenary is fed from the ac transmission grid through a number of equally spaced substations, designed in such a way that voltage drops are acceptable in case of single contingencies. Each substation will be equipped with multilevel VSCs based on PWM-switched IGBTs. At the ac side, the VSC can inject or absorb reactive power, while the remaining degree of freedom can be used to control either the exchanged active power or the dc voltage. This has already become a mature technology which is finding new applications in niches formerly reserved to classical thyristor-based converters.

Substation

The core of the traction substation in the proposed paradigm is shown in Figure 6. It is composed of a three-phase modular multilevel

VSC connected to the power system through a step-down transformer. The multi-level topology shown in Figure 7 is suitable for the power range required in this traction application. Modularity, reduced switching frequency due to the multilevel architecture and redundancy are some of the main features of this topology. Note that the ac input voltage of the VSC (15 kV) has been selected to obtain a dc voltage around 24 kV. This is discussed in Section III-D. Therefore, using a multi-level converter composed of 24 modules per phase, each made up of 4.3 kV/1200 A IGBTs, it is possible to inject up to 30 MVA into the 24-kV dc bus. Each substation is composed of a pair of these units due to reliability issues.

Cable and Wire Layout

Regarding the cable and wire layout, main advantages of the proposed dc electrification system stem from: 1) null reactance, leading to considerably reduced voltage drops, and 2) null skin effect, increasing the rail net conductance. Consequently, it is possible to reduce the number of wires used for the return current in ac electrification systems represents the proposed wire and cable layout for the 24-kV dc electrification where a considerable simplification is achieved.

DC-DC Interconnections

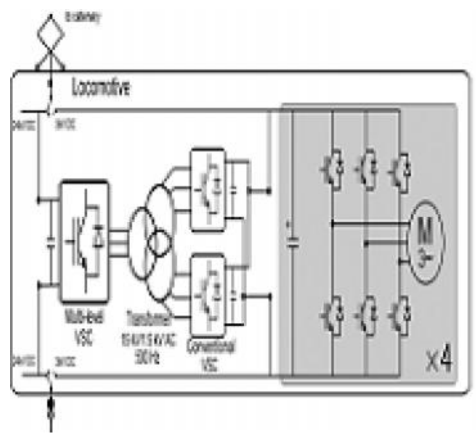
In large cities it is very frequent for high-speed, long-distance lines to run very close to or even share the railroad right-of-way with metropolitan or short-distance dc lines. In those cases, urban rectifying substations could be virtually eliminated, or at least their number significantly reduced, by strategically locating dc-dc links between the 24-kV and the 3-kV dc electrification systems. For this purpose, the bidirectional, isolated dc-dc converter shown in Figure 9 can be used. On the 24-kV side, a multilevel inverter, similar to that used in the traction substation is in charge of generating a high-frequency (e.g., 500 Hz) ac voltage, allowing the use of a more compact transformer to adapt the voltage levels. The ac-dc conversion can be done by means of conventional VSCs based on 6.5-kV IGBTs, similar to those used in actual dual-voltage locomotives.

Hardware Implementation

This subsection is devoted to analyze the performance of the proposed electrification system in terms of normal and N-2 contingency operation regarding the voltages and delivered power. The voltage profile of the railroad and the power delivered by each substation corresponding to normal and N-2 contingency operation. The maximum power of each substation is 60 MVA and the minimum allowable voltage is assumed to be 18 kV (0.75 p.u., similar to the limit imposed to the 25 kV ac).

In normal operation, the analysis shows that when the traction substations maintain the

Figure 1: Power Circuit



voltage to the rated value, the voltage drop is quite reduced, despite 24 kV dc being used (roughly one half of the 50 kV used in the ac electrification system). Moreover, all the substations evenly contribute to supply the power demanded by the rolling stock. The slight differences between injected powers depend on the relative distances of the traction loads with respect to each substation, as a local voltage control is assumed.The worst outage condition in terms of voltage drop corresponds to the loss of one of the substations at the end of the railroad, in which case the nearest (penultimate) substation has to feed a maximum of 6 trains located along the last 180 km. Assuming the voltage setpoints of the healthy substations remain constant, Figure 14 shows that the resulting voltage drop is within permissible values. The situation could be improved if the voltage setpoint of the adjacent substation was appropriately raised by the REMS secondary.

Comparison of Infrastructure Requirements

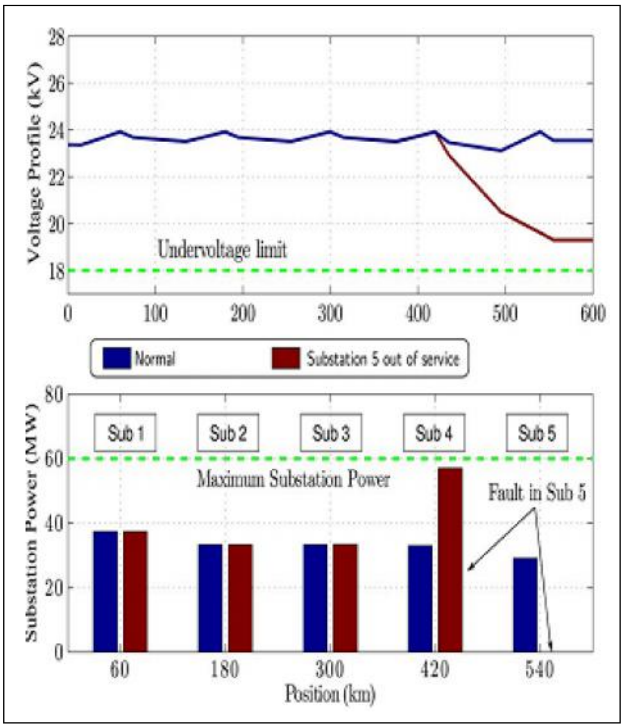
The Table compares the infrastructure requirements corresponding to the 2 25 kV ac electrification and the proposed 24 kV dc scheme, both of them schematically illustrated in Figure 13. The reader is referred to the electrification design details (rated power, distances, etc.), provided in Table 1. Note that the total installed power corresponding to the ac substation transformers is 1440 MVA to supply a maximum of 160 MW demanded by the rolling stock. The N-2 criterion (single substation out of service) is satisfied comfortably without railroad traffic interruption with this infrastructure. On the other hand, in the proposed dc electrification the entire railroad constitutes a unique sector, so that all the substations can share the power demanded by the rolling stock. Therefore, the total installed power can be better adapted to the actual power demand. In this example, it is sufficient to install 5 substations, each with half the installed power of those in the ac electrification. This reduced installed power suffices to withstand the N-2 criterion (loss of a traction substation) as shown by simulation in the next subsection.

Main advantages of the proposed paradigm can be summarized as follows:

- Intrinsic balanced operation at unity power factor of individual railway substations. There is no need of STATCOMs or load balancing converters. In fact, the VSCs could inject reactive power to the ac system if required.
- Simplicity of substations and stationary power equipment, allowing plug-and-play modular connectivity to a larger extent than among existing heterogeneous subsystems.
- Simplicity of rolling stock. Typically, several rated voltages coexist and even overlap in the same geographical area (sometimes owing to historical reasons), which forces many trains to be presently equipped with dual-voltage systems.

Advantages of the Proposed VSC-Based Paradigm

- Catenaries without neutral sections. Unlike single-phase ac catenaries, which are split in sectors owing to the 120 phase difference between neighbour substations, the dc catenary can be electrically a single distributed bus, no matter how long the



railway is. This reduces the voltage drop and facilitates the operation of the healthy system without interruptions in case of failure of a single substation. Note that several dc catenaries could be eventually interconnected, either in radial structures or even forming loops, so long as they share the same rated voltage.

- Catenaries with 40% more power capacity than ac ones for the same peak voltage and current. Furthermore, the lack of catenary reactance significantly reduces the voltage drop, allowing substations to be further away.
- The incorporation of distributed renewable resources is facilitated. In remote rural areas (e.g., in countries like India or China), the presence of such renewable sources could allow electrification of railways without having to deploy an ac transmission system, which is the main reason why diesel-based locomotives are still used in those environments. Just to give a rough idea of the potential synergy behind this possibility, consider a line of PV modules, one-metre wide, running along a 400-km railway. This yields 40MWof PV peak power, capable of providing about 60 GWh/year in countries like Spain. Fast acting storage devices can be also attached to the MVDC system for transient support of energy balance. In case of need, the dc bus could even play the role of conventional distribution networks for small isolated villages (microgrids).
- Regenerative braking and bidirectional exchange of energy among all of the involved subsystems is facilitated, compared to existing railways systems. In some cases, strategically located dc-dc links may be sufficient to feed the metropolitan trains from the trunk MVDC system, preventing in this way the need to deploy additional substations within congested urban areas.

Simulation of the Proposed System

Using MATLAB software the Isolated ZVT boost converter is simulated for both open loop circuit and closed loop circuit. the simulation

Figure 2: Proposed System Simulation

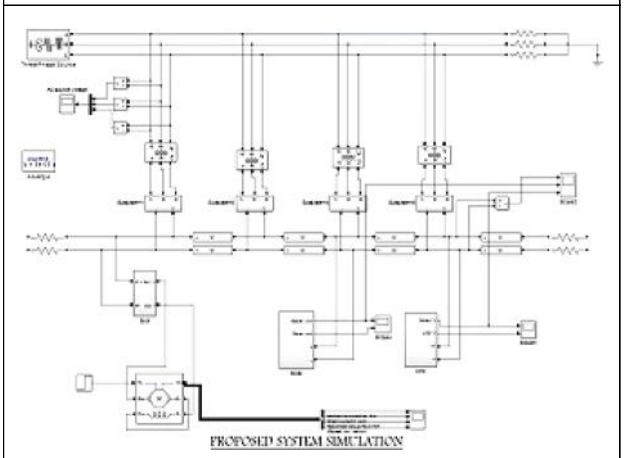


Figure 3: Solar Panel

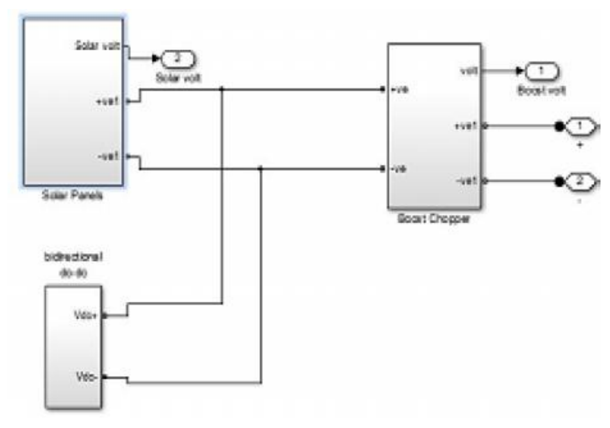
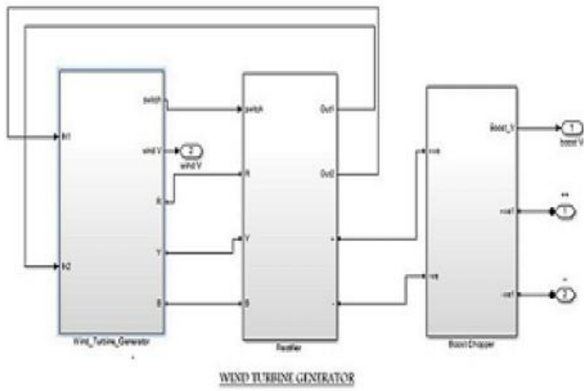


Figure 4: Wind Turbine Generator



results of the proposed converter with output disturbance applied at the time instant of t.

HARDWARE DETAILS AND PHOTOS

Figure 5: Hardware Kit

Operation

This Project initially starts functioning from the PIC (Peripheral Interface Controller) which receives input supply of 11 V-13 V from transformer and Solar panel. PIC controller sends the controlled level of supply (5 V) to the driver circuit, which thereby converts the electric supply in the form of signals. Those

Figure 6: Output Results

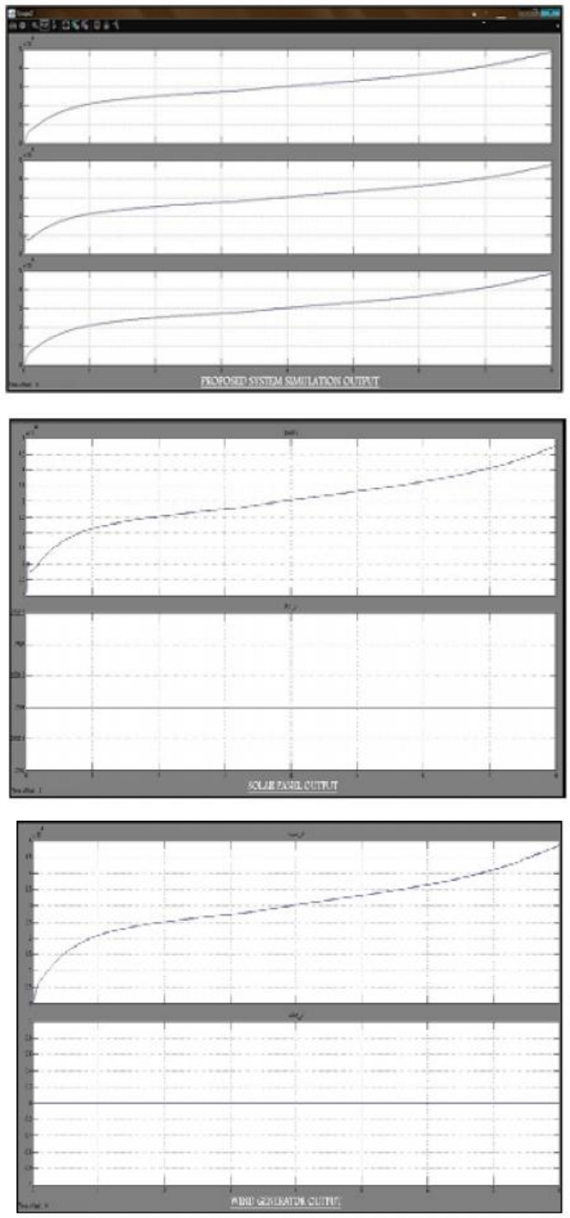
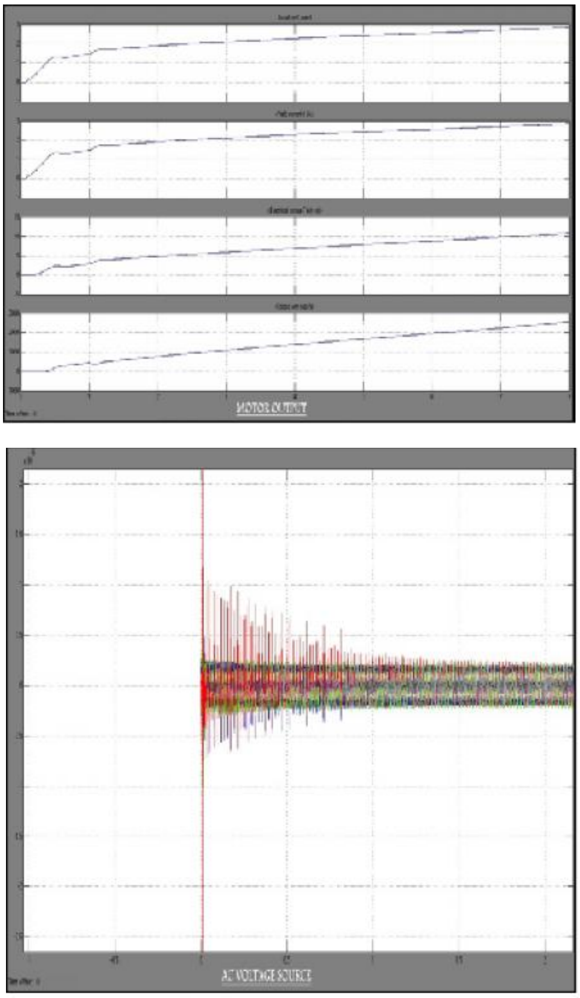


Figure 6 (Cont.)



signals are sent to Boost chopper which stimulates the gate pulses and boosts the voltage level to upto 15 V. Hence this voltage supply can be able to run the DC motor.

CONCLUSION

This work envisages a railway system composed of an interconnected network of dc subsystems (ideally comprising at most two rated voltages, 3 and 24 kV), capable of exchanging energy in a versatile and modular fashion among the bulk ac transmission system, mobile loads (trains), renewable generators and storage devices. This way, the railway infrastructure becomes a distributed energy hub, which can be viewed as a dc super microgrid spanning a large geographical area. The basic building block of the proposed paradigm is the VSC, which constitutes the natural interface between the dc bus and the ac systems (both the ac external grid and the locomotive motors). Besides proposing a new MVDC paradigm for railway electrification.

This work introduces two novel locomotive designs intended to seamlessly run in both 3-kV and 24-kV dc systems. Some building blocks found in these locomotives are shared by dc-dc bridges, which can be useful in places where high-speed, high-voltage routes get close enough to, and consequently can directly feed, urban transportation systems. Advantages of the proposed framework, with respect to the standard 2 25 kV ac system, have been shown both qualitatively and numerically, through an existing high-speed railroad in Spain. These include less installed power and complexity of the railroad infrastructure for the same traffic, simpler and modular locomotive designs and more friendly integration in the ac transmission grid. Possible drawbacks are related with the fact that ac/dc and dc/dc multilevel converters are still under development, and the need to deploy more costly protection and switching equipment.

REFERENCES

1. Adapa R (2012), “High-Wire Act: HVdc Technology—The State of the Art”, *IEEE Power Energy Mag.*, Vol. 10, No. 6, pp. 18-29.
2. Awasty H D (1964), “Railway Electrification in India”, *Proc. Inst. Elect.*

Eng., Vol. 111, No. 4, pp. 833-848.

3. Bakran M M, Eckel H G, Eckert P, Gambach H and Wenkemann U (2004), “Comparison of Multisystem Traction Converters for High-Power Locomotives”, in Prco. 35th IEEE Power Electron, Specialists Conf., Vol. 1, pp. 607-703.

4. Bhargava B (1999), “Railway Electrification Systems and Configurations”, in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Vol. 1, July 18-22, pp. 445-450, Edmonton, AB, Canada.

5. British Transport Commission (1956), “The System of Electrification for British Railways”, Westerham Press Ltd., London, UK.

6. Chen X, Sun H, Wen J, Lee W J, Yuan X, Li N and Yao L (2011), “Integrating Wind Farm to the Grid Using Hybrid Multiterminal HVDC Technology”, *IEEE Trans. Ind. Appl.*, Vol. 47, No. 2, pp. 965-972.

7. Council Directive 96/48/EC of July 23, 1996 on the Interoperability of the Trans-European High-Speed Rail System.

8. Directive 2001/16/EC of the European Parliament and of the Council of March 19, 2001 on the Interoperability on the Trans-European Conventional Rail System.

9. Freeman R and Cooper H (2005), “Why Electrified Rail is Superior”, *21st Century Sci. Technol.*, Vol. 18, No. 2.

10. Leander P and Ostlund S (1989), “A Concept for an HVDC Traction System”, in Proc. Int. Conf. Main Line Railway Electrif., September, pp. 169-173.

11. Steimel A (2012), “Under Europe’s Incompatible Catenary Voltages: A Review of Multi-System Traction Technology”, in *Elect. Syst. Aircraft, Railway Ship Propulsion*, October 16-18.

12. Wojtas B J (1989), “Developments on British Railways Traction and Rolling Stock”, *Power Eng. J.*, Vol. 3, No. 2, pp. 95-102.

13. Yongzhao P, Maoxiang L and Jiangtao L (2010), “Reducing Energy Consumptionin China’s Railway Freight Transportation”, Presented at the *WASE Int. Conf. Inf. Eng.*, August 14-15, Beidaihe, China.