The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 7.8
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.7.8

Efficient utilization of regenerative braking energy in bilateral co-phase systems

N. Pande and T. Koseki

**Department of Electrical Engineering and Information Systems,
Graduate School of Engineering, The University of Tokyo,
Japan**

Abstract

This paper takes the example of Indian Railways to show efficient utilization of regenerative braking energy(RBE) in bilateral co-phase systems. Indian Railways traction supply comes from the public utility grid. With the increase in three-phase locomotives there is an enhanced feedback of RBE to the grid especially when there is no available locomotive to absorb this RBE in the same feeding power sector. This often leads to impact on the utility grid (due to the harmonics in RBE) and presently there is no provision to account for the energy flowing back to the grid in the energy bill. Thus it becomes imperative to efficiently utilize this RBE in the railway network itself. In our work we model 25kV, 1-ø, AC traction system of Indian Railways and demonstrate the energy saving achieved by modifying the existing traction power system to bilateral co-phase system. We also demonstrate the importance of immediate switching over to 3-ø, regenerating locomotives by showing an energy saving of 1.93%. We show an additional energy saving of 0.28% by adopting bilateral co-phase system. We further show the dependence of energy saving on power angle(difference of voltage angles) between adjacent traction sub-station(TSS). Trains are power loads and determining voltages and currents drawn by trains is therefore a non-linear problem. In order to model our approach, we employ conventional iterative Newton-Raphson(NR) load flow method(due to non-linearity) to evaluate voltages, currents and energy saving. This approach also takes care of line losses, due to line impedance, and is accurate. The implementation is complex as compared to traditional power systems because of the presence of moving train loads. This leads to time-varying inter-bus impedance at every instant. The TSS crossing points also dynamically change the inter-bus configuration as TSS is treated as a fixed slack bus. Further, in the proposed bilateral supply system the two TSS are part of a single power network and NR algorithm is modified to take care of two distributed slack buses. The results we obtain show that a net energy saving of at-least 2.21% is achievable and prove the efficacy of our approach.

Keywords: regenerative braking energy, neutral section, Newton-Raphson load flow, bilateral co-phase system, power angle, slack bus, Indian Railways

1 Introduction

As a part of the 2015 international Paris Agreement on climate change, India has pledged a reduction in emissions intensity of 33-35% by 2030 from 2005 levels. Indian Railways(IR) is expected to play a key role in this aspect. IR is currently the world's second largest railway network and is the single largest consumer of electricity in India, consuming about 2% of the country's total power generation[1]. Out of this energy consumption, almost 90% energy is utilized as traction energy.

IR has completely switched over to production of energy efficient electric locomotives with regenerative features[2].With the advent of regenerative locomotives in IR, there is an increase in regenerative braking energy(RBE) in the traction network. Often this energy is utilized by trains present in the same feeding power sector where this RBE is generated. Presently this regenerated energy gets used up by an accelerating train which is in the same feeding section of a traction sub-station(TSS) as the regenerating train. The power cannot flow to the adjacent feeding section of another TSS due to the presence of neutral section(NS) which is an electrically dead section provided to segregate two supplies having different phases. Therefore, if multiple trains are regenerating and no trains are present to absorb the RBE, this energy gets fed back to the utility grid. This may impact safe operation of the grid. Further, this return flow of energy is not accounted for in the energy bill. By utilizing this RBE in the traction network itself, maximum power demand at TSS will reduce and energy will be saved.

Several solutions have been proposed to adequately utilize the RBE of traction power supply systems. These are mainly categorized into three groups(Figure 1): timetable optimisation[3], transporting power across the neutral section[4,5] and elimination of neutral sections[6]. In context of IR, time-table optimisation is not very relevant because IR runs certain premium rakes at priority over other rakes, also fog season, spanning three months, disrupts the timetable totally and freight trains are non-timetabled. Transporting power across the NS involves installation of Railway Static Power Conditioners(RPCs) which are not viable economically and in view of space constraints. Elimination of NS involves installation of Static frequency converters(SFCs) which is again economically not viable for existing TSS.

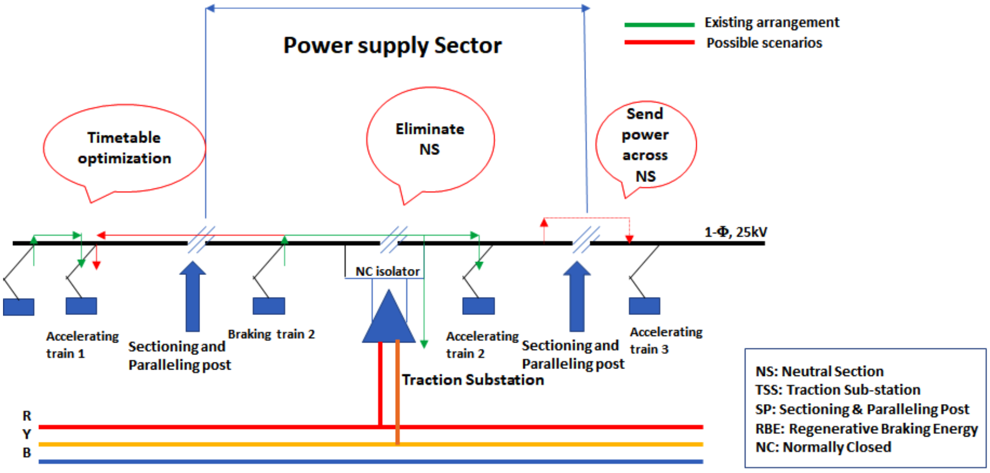


Figure 1: RBE utilization along the railway line in context of IR.

2 Methods

We clearly demonstrate by simulation of a case study on IR that energy saving of at-least 2.21% is possible. The existing and proposed scheme are shown in Figure 2 and Figure 3 respectively. The advantages are shown in Figure 4.

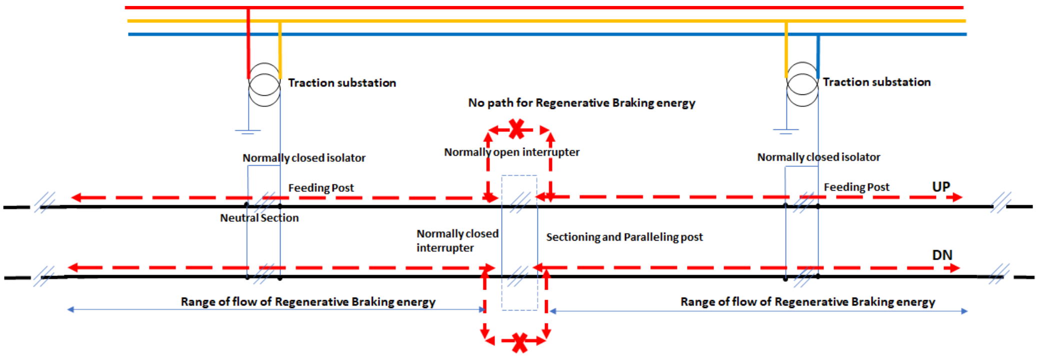


Figure 2: IR Power supply installation network and range of flow of RBE.

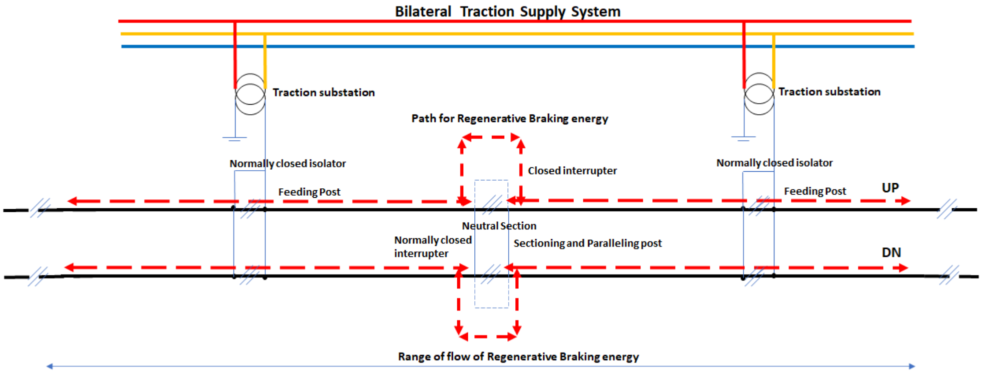


Figure 3: Bilateral co-phase supply and range of flow of RBE.

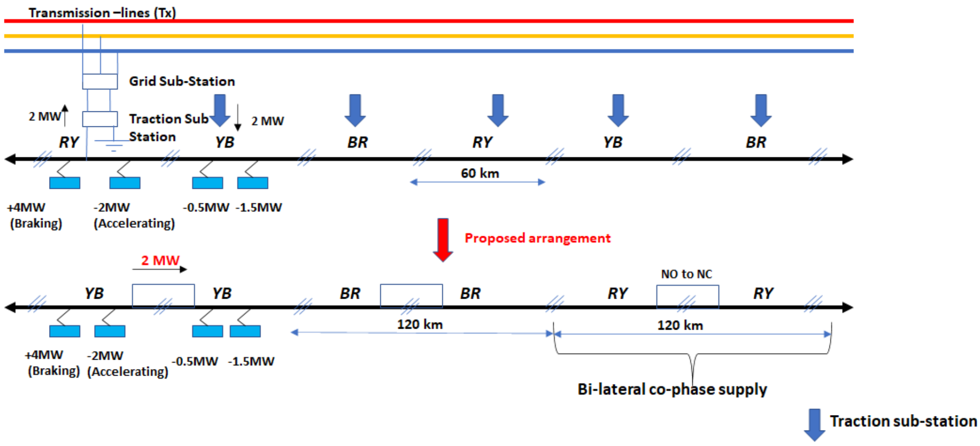


Figure 4: Comparison of Existing traction system and Proposed Bi-lateral co-phase supply system.

It can be seen that the range of RBE distribution is effectively doubled and 2MW power is saved(Figure 4). We perform simulations on MATLAB using NR load flow. Figure 5 shows flowchart depicting the procedure adopted using Dynamic programming(DP)[7].

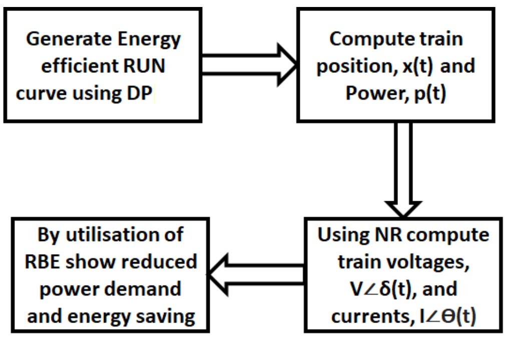


Figure 5: Flowchart for comparing RBE in existing and proposed topology.

Train loads are power loads, so determining currents is a non-linear problem and we employ NR method for an n-bus system[8], having quadratic convergence to calculate powers drawn from the TSS(Figure 6). Existing approaches[9,10] linearize the network and considers trains as current-based loads. We model the trains as power-based loads. Consider Figure 7 and Figure 8. Trains move from station A(x_a) to B(x_b). We bifurcate A-B into 2 regions R_k, feeding region of $TSS_k(x_{tss\_k})$ and R_{k+1} for $TSS_{k+1}(x_{tss\_k+1})$. Let x_{ns_k} be the location of intermediate NS.

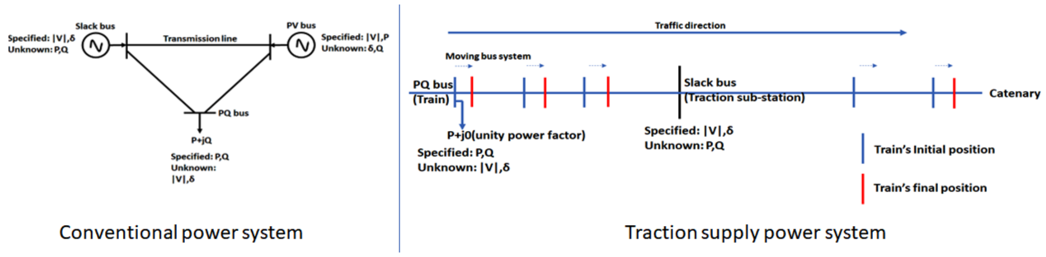


Figure 6: Newton Raphson based load flow technique.

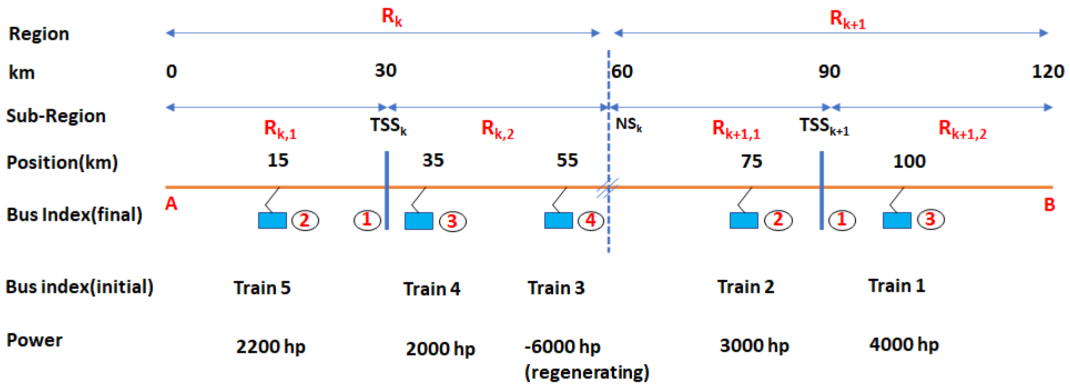


Figure 7: Example case with existing traction power supply system.

Figure 8: Example case with proposed traction power supply system.

Consider region R_k. Let $x_i(t_i)$ denote location of train T_i at time t_i.

$$x_i \varepsilon R_{k,1} \leftrightarrow x_a < x_i \leq x_{tss\_k} \quad (1)$$

$$x_i \varepsilon R_{k,2} \leftrightarrow x_{tss\_k} < x_i \leq x_{ns\_k} \quad (2)$$

$$d_{Ti} = |x_{tss\_k} - x_i| \ \forall\ T_i \varepsilon R_k \quad (3)$$

$$\text{Let } k_{min11} = \text{index}(\text{minimum}(d_{Ti}))\ \forall\ T_i \varepsilon R_{k,1} \quad (4)$$

$$k_{max11} = \text{index}(\text{maximum}(d_{Ti}))\ \forall\ T_i \varepsilon R_{k,1} \quad (5)$$

Where index denotes initial train index.

Let there be m_1 buses in $R_{k,1}$ and m_2 buses in $R_{k,2}$. TSS_k is labelled as slack bus(1). Train(d_{T_kmin11}) is bus(2), next is bus(3) and so on, Train(d_{T_kmax11}) is bus(m_1+1).

$$\text{Let } k_{min12} = \text{index}(\text{minimum}(d_{Ti}))\ \forall\ T_i \varepsilon R_{k,2}$$
$$\text{index}(d_{T\_kmin12}) = (m_1+1)+1. \quad (6)$$

$$Z_{Ti} = z_c \text{ x } |x_{tss\_k} - x_i|\ \forall\ T_i \varepsilon R_{k,1} \quad (7)$$

Where z_c is the complex characteristic catenary impedance.

$$Z_i = \{Z_{Ti}\}, \text{ sorted in ascending order} \quad (8)$$

Inter-bus impedance is,

$$\text{Bus}_2 - \text{Bus}_1 : Z_1$$
$$\text{Bus}_{j-1} - \text{Bus}_j : Z_j - Z_{j-1}\ \forall\ j\varepsilon(3,m_1+1) \quad (9)$$

The above is repeated for $R_{k,2}$.We compute [V,δ] at each bus using Equation 10

$$\Delta X = J^{-1}M \quad (10)$$

Where, $\Delta X = [\Delta\delta\ \Delta V]^T$ and $M = [\Delta P\ \Delta Q]^T$, J is the Jacobian matrix.

For proposed system we have two slack buses(2 TSS). The approach is similar as above. Table 1 shows the re-indexing for example in Figure 7 and Figure 8.

Existing/Proposed			
Initial_index	Final_index	linedata	Voltage
TSS_{k+1}	1/5		25.00/25.00
1	3/7	1-3/5-7	24.83/24.83
2	2/6	1-2/5-6	24.80/24.99
TSS_k	1/1	/4-6	25.00/25.00
3	4/4	3-4/3-4	25.52/25.24
4	3/3	1-3/1-3	25.06/25.01
5	2/2	1-2/1-2	24.86/24.86

Table 1: Busdata and linedata(existing/proposed system)

3 Results

We consider 20 trains running from A-B with headway of 10 minutes(Figure 9). Figure 10 shows an improvement in voltage profile for the Mail Express I train I using proposed topology. Figure 11 and Figure 12 shows the power profiles of TSS_k and TSS_{k+1} with power angle($\delta = \delta_{k+1} - \delta_k$), $\delta = 0$ and $\delta = -5^{\circ}$. Initially there are no trains in feeding section of TSS_{k+1}, so there is no power drawn. We can see the impact on power demand reduction by having energy regenerating locomotives. Further, as most of the regenerative braking occurs in feeding region of TSS_{k+1}, therefore clearly maximum power demand is reduced as evident from Figure 11. The results show a saving of 1.93% if all electric locomotives in IR are equipped with regenerative braking feature and further saving of 0.28%(total 2.21%) by adopting bilateral traction supply system as proposed in our work. This work considers an ideal scenario with no gradients and energy-saving driving to determine minimum energy savings possible. Practically, savings from RBE will be much more. The dependence of energy saving on power angle can be seen in Figure 13. Further, Figure 11 and Figure 12 also show that when $\delta \neq 0$, there are circulating currents which offset any saving by RBE. When $\delta \approx 0$, there is energy saving(Table 2).

There is energy saving for TSS_{k+1} in voltage leading because most trains start in feeding section of TSS_k and therefore there is no power flow from TSS_k towards TSS_{k+1} at leading TSS_{k+1} voltage. Infact some initial power requirement is met by TSS_{k+1}. However, if this power angle exceeds certain value, again circulating currents become dominant and offset any saving by RBE. Techniques exist in literature to reduce the power angle[11]. However, these are beyond the scope of this paper.

TSS / Energy(kWh)	TSS_k	TSS_{k+1}	Total	0.75x(RBE savings)	Proposed Scheme savings
Without RBE	24994.19	15538.44	40532.63		
Existing system with RBE	24319.10	15194.38	39513.48	764.36 (1.93%)	111.21 (0.28%)
Proposed system with RBE(δ=0)	24992.99	14409.27	39402.27		
Proposed system with RBE(δ= -5˚)	33627.94	11044.24	44672.18	764.36 (1.93%)	-5158.69 (-13.06%)

Table 2: Energy saving results.

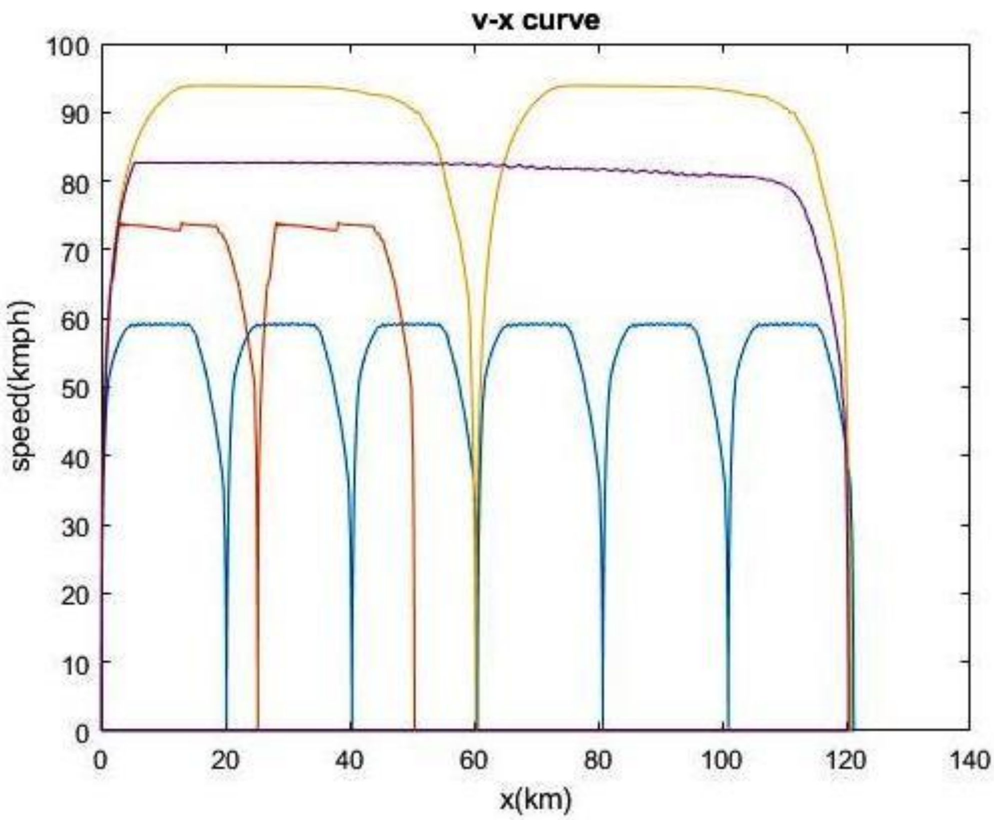


Figure 9: Speed-distance curves.

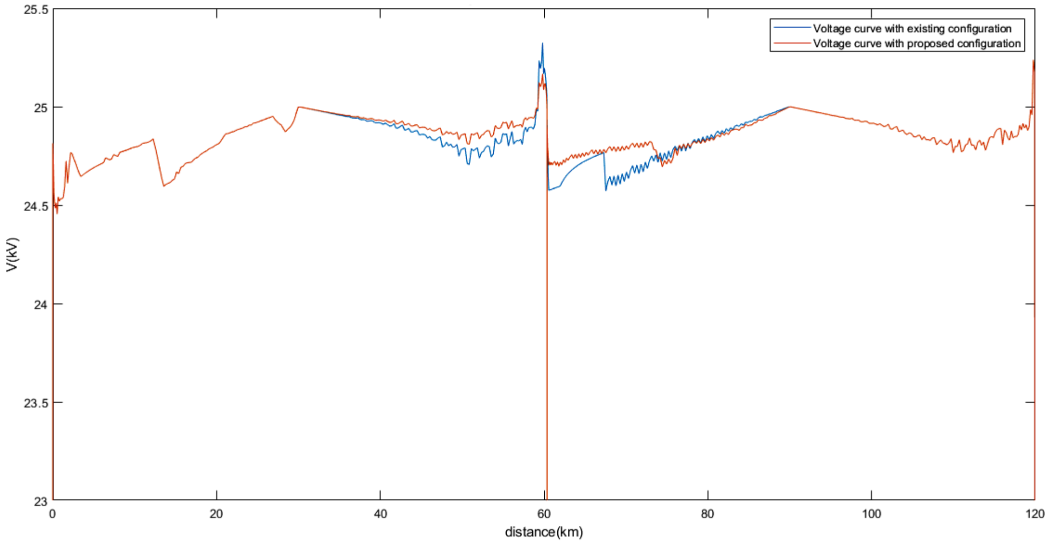


Figure 10: Voltage profile improvement for Mail Express I.

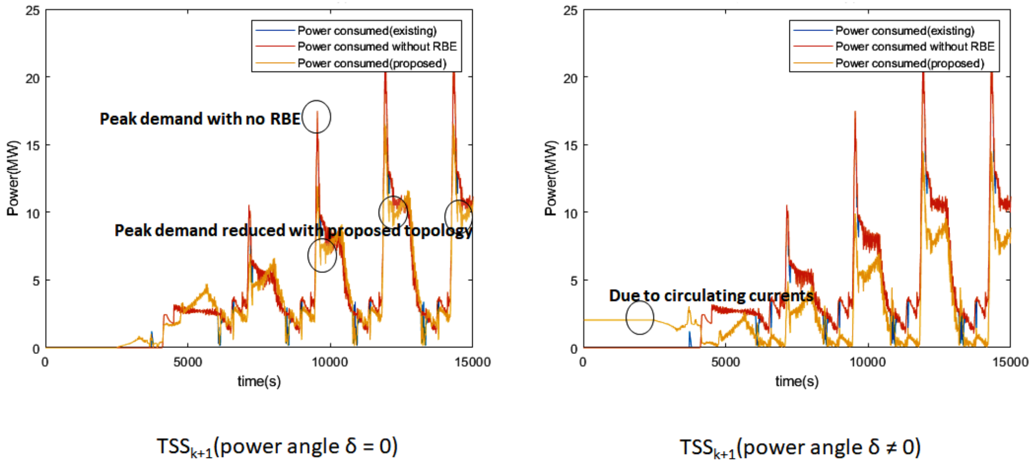
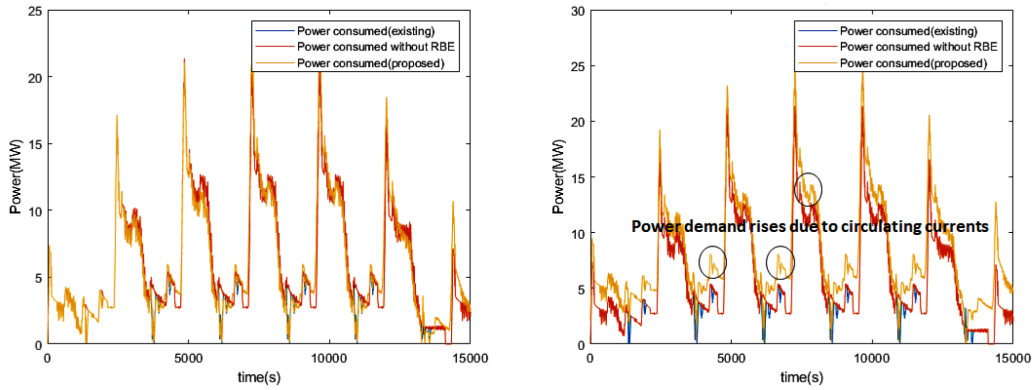


Figure 11: TSS$_{k+1}$ Power-time profile for $\delta = 0$ and $\delta = -5^{\circ}$.



TSS$_k$(power angle δ = 0) TSS$_k$(power angle δ ≠ 0)

Figure 12: TSS$_k$ Power-time profile for $\delta = 0$ and $\delta = -5^\circ$.

.

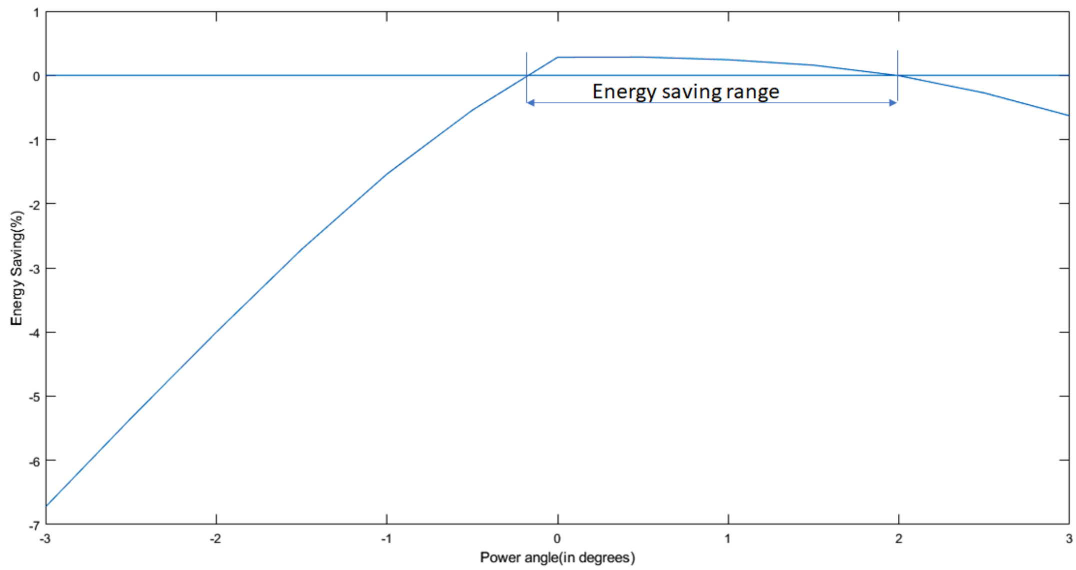


Figure 13: Energy saving(%) variation with power angle.

4 Conclusions and Contributions

A novel scheme is described to attain maximal utilization of RBE along the railway line by converting the existing traction network to bilateral co-phase network. The scheme is economical as there is no addition of any new equipment compared to existing techniques. Further, conventional NR power-based method is applied to solve for voltages and currents by means of a novel algorithm. The proposed approach is more accurate as it models the trains as power loads as opposed to current loads adopted in existing literature. The scheme presented here is generic and can be applied to any number of trains and any type of section(with gradients and speed limits). The energy dependency on power angle is crucial and techniques to minimize it using existing system shall be discussed in future works. Further, in future, the authors plan to extend the above scheme for 1-ø, 25kV AC double line sections and 2x25kV AC traction power network of high-speed railways.

Some important contributions of this paper are modelling of bilateral power supply system for Indian Railways using the existing infrastructure and demonstrating the relationship between effective RBE utilization and power angle. It is clearly shown that the power angle, $\delta \approx 0$ for energy saving otherwise any saving is offset by circulating currents.

The impact of running all locomotives with regenerative braking feature on energy saving is clearly brought out. We have assumed in our energy calculations that 75% locomotives are yet to be converted to regenerative type. Further, additional saving achieved by adopting bilateral supply system is demonstrated.

The trains are analyzed as moving PQ bus systems and the TSS are modelled as slack bus systems analogous to conventional power systems and NR load flow technique is applied to determine $[V,\delta]$ at each bus. A new algorithm is written for comparing the existing and modified bilateral supply configurations. Further, conventional Newton-Raphson method does not deal with multiple slack bus system and is modified to accommodate the same for bilateral supply system. In the knowledge of the authors, such application of NR on traction supply system is novel.

Acknowledgements

The authors are grateful to Indian Railways, Government of India for providing the field data and facts and figures used in the present study. Nipun Pande is also thankful to MEXT, Government of Japan for financially supporting him.

References

[1] "Decarbonisation of Indian Railways", A CPI Report, 2017.

[2] "Green Railways", A Report by Indian Railways, 2021.

[3] X. Yang, B. Ning, X. Li, T. Tang. “A two-objective timetable optimization model in subway systems”. IEEE Trans. Intel. Transp. Syst., 15, 1–9, 2014.

[4] K.Aoki, K.Kikuchi, M.Seya and T.Kato,"Power Interchange System for Reuse of Regenerative Electric Power", Hitachi Review Vol. 67, No. 7 834–835, 2019.

[5] Z. Gao, Q. Lu, C. Wang, J. Fu, and B. He, “Energy-Storage-Based Smart Electrical Infrastructure and Regenerative Braking Energy Management in AC-Fed Railways with Neutral Zones,” Energies, vol. 12, no. 21, p. 4053, Oct. 2019.

[6] M. Ufert, “Static frequency converters in 50 Hz traction power substations”. eb - Elektrische Bahnen INT. 114. 414-419, 2016.

[7] M. Miyatake, H. Ko.“Optimization of Train Speed Profile for Minimum Energy Consumption”. IEEJ Trans Elec Electron Eng, 5: 263-269, 2010. https://doi.org/10.1002/tee.20528

[8] A. Chandan. “IEEE 30 BUS Newton Raphson Load Flow Analysis”. https://www.mathworks.com/matlabcentral/fileexchange/58884-ieee-30-bus-newton-raphson-load-flow-analysis, MATLAB Central File Exchange. Retrieved April 30, 2022.

[9] C.J. Goodman, T. Kulworawanichpong. “Sequential linear power flow solution for AC electric railway power supply systems”. Proc int conf on computers in railways(Computers in Railway VIII); p. 533–7540, 2002.

[10] T. Kulworawanichpong. “Multi-train modeling and simulation integrated with traction power supply solver using simplified Newton–Raphson method”. Journal of Modern Transportation. 35.10.1007/s40534-015-0086-y, 2015.

[11] L. Zhang, X. Li, S. Liang, D. Han. “Research on the influence of electric railway bilateral power supply on power system and countermeasures”. International Journal of Electrical Power & Energy Systems. 137. 107769. 10.1016/j.ijepes.2021.107769,2022.