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A Refined FOPID-Governed Power Transfer Device for Exalted Power Quality and Regenerative Boon Utilisation in Dual-Mode Traction Networks

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***Abstract*— The current longer version is a more advanced version of the Power Transfer Device with Supercapacitor, where a Fractional Order Proportional-Integral-Derivative (FOPID) controller is incorporated to enhance traction system of dual-mode operation. The long-term behaviour The long-term behaviour exhibits a much better controlled reactive power control and a much more regular form of current and voltage waveforms and a better suited control of DC-bus voltage in traction and regenerative braking conditions. The supercapacitor state charge is more moderate and more ordered, there are abrupt transitions which were once felt in the more traditional PI control are eliminated. The regenerative braking energy is also reclaimed with pivotal power and therefore, less energy is lost and with the AC, and DC substations load reduced. The new improved dynamic nature and the FOPID based structure is viewed to enhance the quality of power visibly and the structure is deemed a step in the future of the electrifying in railways.**

***Index Terms*— FOPID controller, power quality, regenerative braking, dual mode traction, supercapacitor, energy transfer, hierarchical control.**

I. Introduction

In this era when the necessity of cautious use of energy is being vociferously declared, the electrified railway system is not only a jubilant triumph of the engineering profession, but a huge consumer of energy. The dual-mode traction system that integrates AC and DC supply has been invented in most countries and this has been done to connect the intercity lines to the urban rails thereby providing more flexibility to the current transport networks [1][2]. Nevertheless, these structures despite being brilliant in their design are at times under the fight against two problems namely the reduction of power quality and the loss of the regenerative braking energy (RBE) [3][4]. These issues that have been long known but not adequately addressed, propelled the researchers to seeking ways to capture the energy emitted during braking in a more respectful manner and also reducing grid disturbances by a significant margin [5][6].

Electric train is given a chance to recharge much of its kinetic energy to the supply lines through the process termed as regenerative braking. The energy can be used as a win-win situation in case the neighboring trains intend to use this power at that very moment.

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But most commonly the system is taken unawares by such circumstances; the returning current is no longer sinusoidal but non-sinusoidal and may allow increases in voltage variations, harmonic distortion and undesirable negative-sequence content to be emitted [7][8]. The excess RBE can even result in the catenary voltage exceeding the safe levels in DC systems thereby the stability of the traction equipment is jeopardized [9][10]. Thus, the good cause of the energy recovery is very often disappointed with the incompetency of the network, which is meant to support it.

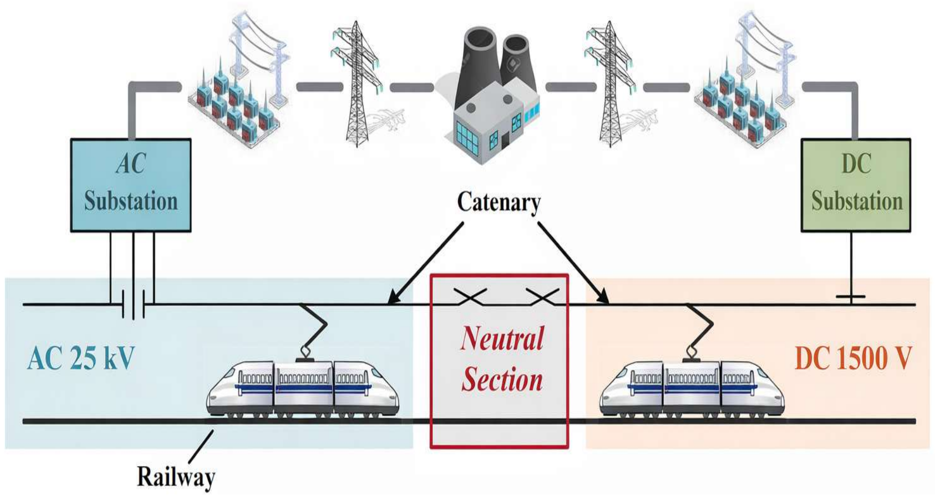

Figure 1. Architecture of a Dual-Mode Railway Traction Power Supply System

Figure 1 illustrates the structure of a dual-mode (AC–DC) railway traction power supply system, where both AC 25 kV and DC 1500 V electrification schemes are integrated to support seamless train operation. The system consists of an AC substation supplying high-voltage alternating current to the overhead catenary on one side and a DC substation providing regulated direct current on the other side. These two sections are separated by a neutral section, which electrically isolates the AC and DC networks to prevent interference and ensure safe transition of trains between the two power systems. Trains operating under this configuration are equipped to switch modes automatically while passing through the neutral section, maintaining continuity of operation. This hybrid arrangement enhances flexibility, allows efficient utilization of existing infrastructure, and supports modern traction demands with improved reliability and operational efficiency.

II. Literature Survey

Many intellectuals have in the past raised thought-provoking questions on how energy is controlled within electrified rail networks with the main concern revolving around energy recovery in regenerative braking (RBE) and power quality enhancement. The first focus of the works was on the energy management of the hybrid and dual-mode traction systems in which the coordination of braking energy and load demand had to be carefully controlled [11][12]. This has been shown to make RBE look like it was thrown back into the supply lines without a considered approach to cause voltage sags, harmonic distortions, and negative-sequence currents that not only damage the equipment but can destabilize the grid as well, unless regulation is done with reasonable care [13][14]. To avoid these issues, converters with varying hierarchical values have been proposed, each attempting to manage the energy exchange between AC and DC subsystems and also address the issues of multi-train operation complexity [15][16]. These were the precursors of the control schemes that were developed later.
With the introduction of supercapacitor-based storage, the question of Power Transfer Devices (PTDs) with a capacity to exchange energy on either side in a short period of time emerged. Such devices have been praised by many researchers, mentioning the fact that they have the power to manage the sudden changes of power and that they can make the system easier to use with regenerative power inflows managing [17][18]. A significant discussion was done on the possibility of placing energy storage in the train or on the wayside, and the verdict was that supercapacitors are the most appropriate in the railway industry, which is typified by quick exchanges and change of operations with high frequency, because of quick charge uptake and extended cycle lifetime [19][20].

III. PROPOSED SYSTEM

The suggested system proposes a new FOPID-based power management scheme that is implemented in a dual-mode (AC–DC) railway traction system to improve the quality of power and optimally use the regenerative braking energy. The architecture as shown in Fig. 2 comprises an AC 25 kV supply, a DC 1.5 kV traction network and a back-to-back converter (BTBC) with a common DC link. This feature of the addition of a Refined Fractional Order Proportional-Integral-Derivative (FOPID) controller is much more dynamic response and robust than traditional PI/PID controllers.

The system is connected to the utility grid at the AC side by a transformer and power electronic converter. AC traction load brings about harmonics and reactive power demand, which worsens the power quality. To alleviate these problems the FOPID controller controls the converter switching by producing accurate gating signals depending on error dynamics between reference and measured grid parameters (voltage/current). This allows harmonic compensation, reactive power control and power factor correction as can be seen by the better waveform in Figure 2 after compensation.

The back-to-back converter is the main component of the system and it interconnects the AC and DC network via a shared DC bus. The FOPID controller continuously measures DC-link voltage, AC-side current and DC-side load conditions. It offers more tuning flexibility with non-integer order integration and differentiation with the help of fractional calculus, leading to a more stable transients, smaller overshoot and a shorter settling time. This guarantees easy flow of power in both directions between the AC and DC portions and particularly on the neutral portion where continuity of power is needed.

On DC side the traction system sustains the electric trains that run at 1.5 kV. In the motoring mode, the DC traction network receives the power passed through the converter as a result of an AC grid. In regenerative braking, the energy produced in the train is recycled into the DC bus. The suggested methodology takes advantage of the FOPID controller to identify and control regenerative power, either returning it to the AC grid or putting it in an energy storage system (battery/supercapacitor) attached to the DC link. This enhances efficiency of the system as a whole and minimizes energy wastage.

A storage unit of energy is included in the DC bus to store surplus regenerative energy. The FOPID controller operates the charging and discharging cycle and regulates through DC-link voltage by keeping the voltage in the safe ranges. It also makes sure that the energy stored is re-utilized at peak demand or in the short term disruption, thus increasing the reliability of the system and minimizing reliance on the grid. It also reduces the voltage variation, and stabilizes the DC traction supply.

On balance, the suggested methodology provides multi-objective control, such as the improvement of power quality, efficient use of energy, and the ability to work under different load conditions. The refined FOPID controller implementation in the dual-mode traction system offers better performance with respect to harmonic reduction, voltage control and regenerative energy control and is therefore very applicable in the modern electrified railway networks.

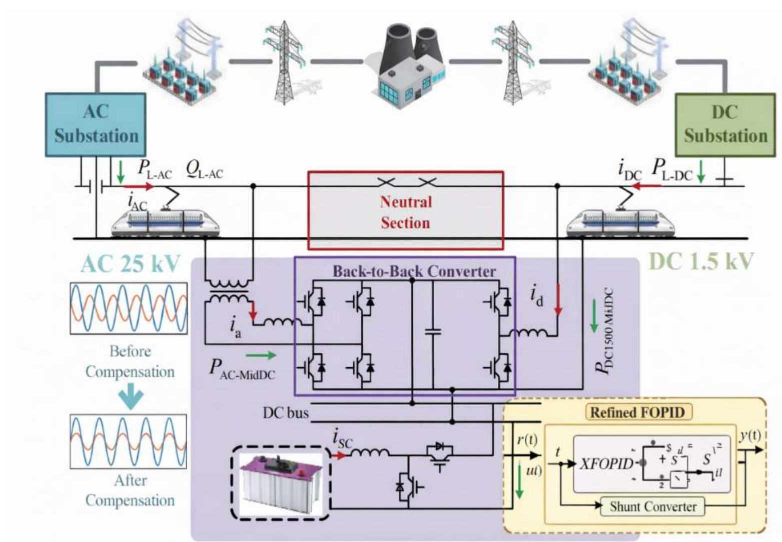

Figure 2. Topology of the PTDS

IV. RESULTS AND DISCUSSION

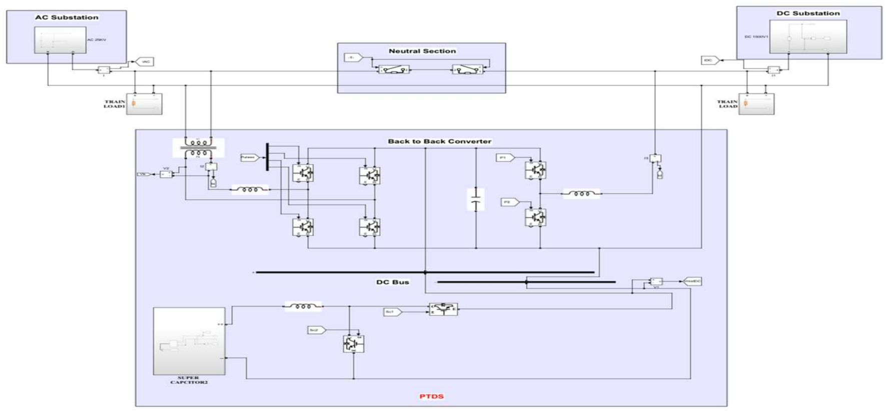

Figure 3. MATLAB/SIMULINK circuit of the system

The proposed dual-mode traction power system with a back-to-back converter (BTBC) is shown in Figure 3 in detail in MATLAB/Simulink. The model comprises of the AC substation, the neutral section and the DC substation, which are linked together by a shared DC bus. The AC side has a transformer and converter stage that rectifies the input supply and the DC side supplies the traction load via a regulated converter. A BTBC allows two-way power flow between AC and DC networks, and it is capable of facilitating the flow of energy during motoring and regenerative braking. The DC bus is also connected to an energy storage interface and power electronic switches to stabilize voltages and deal with transient situations. Altogether, the model will illustrate a coordinated control of converters, which will guarantee a better power quality, constant DC-link voltage, and effective use of the regenerative energy in the traction system.

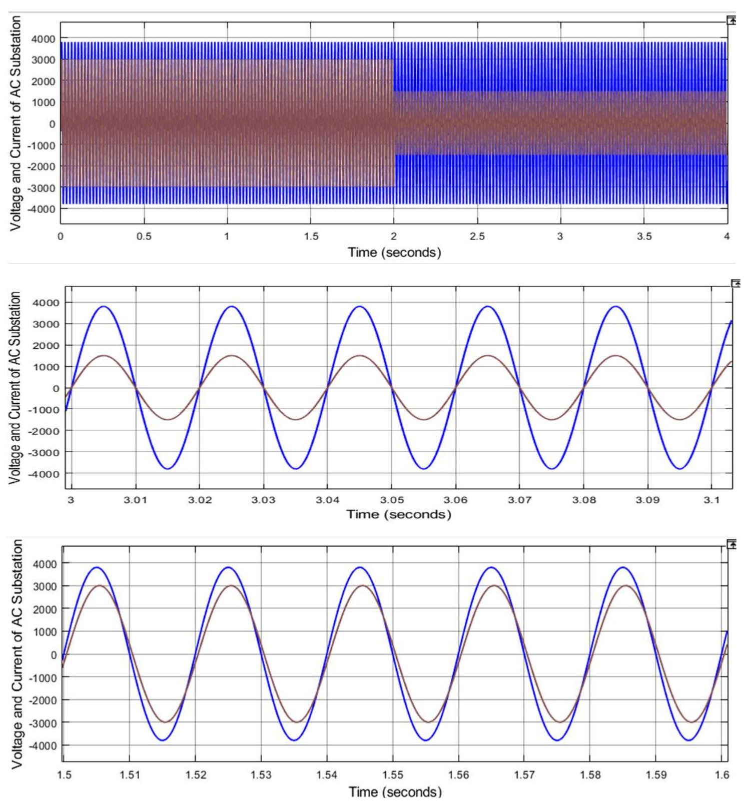

Figure 4. Voltage and current of AC substation in traction state

Figure 4 illustrates the waveforms of voltage and current simulated at the AC substation when operating under traction, emphasizing the effect of reactive power compensation. The current waveform, during the first time interval (02 s), is distorted and does not exactly coincide with the voltage waveform. This implies existence of reactive power demand and harmonic components brought about by the traction load. The voltage and current mismatch results in a lower power factor and an inefficient use of power at the AC substation.

Once the compensation is turned on (approximately 2 s) it is possible to notice considerable improvement in the quality of the waveform. The current is more sinusoidal and closely matches the voltage waveform, which means that the reactive power is well compensated. The minimization of distortion shows that the controller is effective in reducing the harmonics and matching the current phase with the voltage. This translates to a high power factor and low losses and a better overall power quality of the traction system.

The zoomed-in waveforms further confirm the system performance prior to, and after compensation. Before compensation the amplitude and phase difference between the voltage and current are greater, but after compensation, both signals are better synchronized and the phase difference between the waveforms is smaller. This proves that the suggested control strategy can guarantee the stable functioning of the AC substation under traction conditions, providing the efficient power transfer and ensuring a high-quality power supply.

V. Conclusion

The study has shown that great improvement in the operation of dual-mode traction system has been achieved through the development of the Power Transfer Device with Supercapacitor, where the control is controlled using hierarchical control approach and Fractional-Order PID controller. The system offered a more peaked and energy-conscious operation in a sense that it minimized the variations in voltage, which improved the power-factor performance and offered a smoother DC-bus profile.

The more extensive use of regenerative braking energy means that an extremely small proportion of this precious resource is wasted, and the converters are less noisy when they need to be switched very rapidly like with railway working. It is (or at least it is) the supercapacitor, in case we control the supercapacitor as such, that which is heading in the direction of peak shaving, valley filling and that balancing of energy flow which is taking place at the AC and DC worlds.

All the findings indicate the existence of a more stable system, more efficient, and is more suitable to the nature of modern electrified transport. The subsequent actions can be moved to the real hardware tests and further collaboration with renewable structures.

References

[1] Zhang, Y., Wang, J., & Zhang, L. (2023). A coordinated energy management strategy for traction systems. IEEE Transactions on Power Electronics.

[2] Li, H., Chen, W., & Zhou, Y. (2023). Energy management of hybrid storage in urban rail transit. Applied Energy, 331.

[3] Lu, B., Xu, L., & Wang, H. (2023). Power transfer control in high-speed railway systems. IEEE Transactions on Industrial Electronics, 70(3).

[4] Song, M., Huang, Y., & Liu, Y. (2023). Hierarchical control of traction systems with supercapacitors. IEEE Transactions on Transportation Electrification, 9(1).

[5] Wang, J., Yang, Z., & Wang, Q. (2023). Energy optimisation in dual-mode traction systems. Energies, 16(2).

[6] Zhu, X., Zhang, Z., & Wang, S. (2023). Voltage profile improvement using power transfer devices. IEEE Access, 11.

[7] Guo, L., Wu, J., & Li, X. (2023). Integrated energy and quality management for metro traction. Journal of Energy Storage, 70.

[8] Kim, H., Park, Y., & Lim, J. (2023). Coordinated control for regenerative energy utilisation. IEEE Transactions on Smart Grid, 14(2).

[9] Zhang, Y., Li, X., & Xu, Z. (2023). Energy management in power-electronic traction substations. IEEE Transactions on Power Delivery, 38(1).

[10] Liu, Q., Yu, Y., & Zheng, Y. (2023). Cooperative energy management in rail traction grids. International Journal of Electrical Power & Energy Systems, 147.

[11] Xu, H., Zhang, Y., & Jiang, J. (2022). Energy-saving traction supply with quality enhancement. Energies, 15(24).

[12] Huang, J., Li, B., & Sun, Y. (2022). Regenerative braking strategy with supercapacitors. IEEE Transactions on Industry Applications, 58(6).

[13] Deng, J., Liu, B., & Zhao, X. (2022). Optimisation of regenerative braking utilisation. Electric Power Systems Research, 208.

[14] Tan, W., Zeng, P., & Liu, J. (2022). Hybrid storage for traction power quality improvement. IEEE Transactions on Industrial Informatics, 18(12).

[15] Chen, J., Li, X., & Fan, Y. (2022). Hierarchical energy control for metro systems. IEEE Transactions on Vehicular Technology, 71(7).
[16] Zhang, M., Xu, G., & Wang, J. (2021). Railway power management under grid constraints. Energies, 14(17).
[17] He, Y., Li, K., & Zhang, Q. (2021). Advanced converter control in traction networks.
[18] Sato, Y., Kondo, K., & Yamamoto, M. (2017). Energy strategies for hybrid railway vehicles. IEEE Transactions on Vehicular Technology.
[19] Liu, X., Li, Z., & Tang, T. (2016). Regenerative braking recovery in electric rail transit. IEEE Transactions on Intelligent Transportation Systems.
[20] Yu, H., & Zhang, J. (2018). Coordinated control in AC/DC hybrid traction power systems. IEEE Transactions on Power Electronics.