Performance enhancement of a high-speed railway supply system with multi module converter: a laboratory prototype model for Indian railways

Venkatasupura Vemulapati[1], Yerram N. Vijaykumar[2], Nagalamadaka Visali[1]
[1]Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University Anantapur (JNTUA) College of Engineering, Anantapur, India
[2]Department of Electrical and Electronics Engineering, Sri Venkateswara College of Engineering and Technology (SVCET), Chittoor, India

Article Info

Article history:

Received Jan 7, 2021
Revised Dec 21, 2021
Accepted Dec 27, 2021

Keywords:

Indian railways
High speed railway network
Back to back converters
Power quality
Multi-modular converters

ABSTRACT

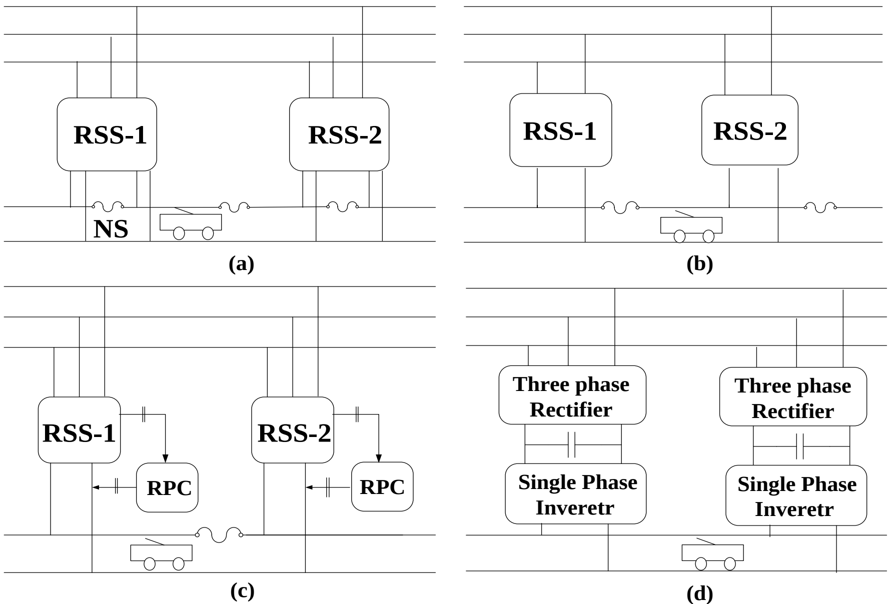
The present Indian traction supply system's complications (neutral sections of the catenary line and issues of power quality) restrict the growth of railway transportation, particularly high-speed rail networks that are fast growing globally. The neutral sections (NS) results in loss of speed, momentum and mechanical failures that are all threatening the fast and stable operation of trains and systems. In the meantime, issues with the power quality such as the negative sequence currents (NSC), the reactive power and harmonics may create problems on the three phase grid side that cannot be overlooked. To address these two issues concurrently, a new traction power supply system is designed in this paper. The proposal will also analyses the theory of operation, build the mathematical model and develop the control system for back to back converters. Small scale prototype is also made for validation of simulation results. The results shows that it can fulfil the practical requirements. The experimental results shows that the overall system is practically more appropriate for the high speed railway.

Corresponding Author:

Venkatasupura Vemulapati
Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University Anantapur (JNTUA) College of Engineering
Ananthapuramu-515002, Andhra Pradesh, India
Email: vvsupura@svcolleges.edu.in

1. INTRODUCTION

Electrical power grids are spread across the nation and are an important part of daily life [1]. Electric railways are common electric power transmission category used to drive passenger and freight locomotives. Some existing traction power supply schemes are presented in Figure 1 [2]. Traction system using balanced transformer is shown in Figure 1(a). The Indian traction supply system is shown in Figure 1(b) which implements a shifting phase order method to deliver power to the train [3]. In general the traction power supply phase will be changing for every 35-40 km due to single phase, nonlinear and arbitrary changing load characteristics of the train. Therefore it is necessary to isolate the areas of various phase sequences, which contributes to the existence of a neutral section (NS), a non-electrical region [4]. The NS leads to loss of train speed and tension in traction power supply [5]. Furthermore, train ramp incidents and traction substation failures (tripping) are already occurring because of these NS [6]. Thus, the quick and stable operation of the train and system is truly required to avoid safety risks. The problem of the NS needs to be addressed in traction, particularly high-speed traction. Many scholars have suggested numerous schemes in response to the difficulties of the NS as presented in Figure 1(c). The continuous power passing through neutral schemes has recently been given more importance [7]. Although those systems are not able to solve the power problems caused by the NS [8], [9]. The Figure 1(d) shows the traction substation model which is most suitable for high speed railway with three phase to single phase power converters and zero NS.



RSS: Railway Substation **NS:** Neutral Section **RPC:** Railway Power controller

Figure 1. Some existing traction power supply schemes using: (a) balanced transformer, (b) phase exchange method, (c) power controllers, and (d) power electrics converters

Power quality issues are another major problem confronted by the AC traction supply system [10]. Non-linear, single-phase and spontaneous fluctuating locomotive loads trigger the power quality problems in the grid [11]. Network and equipment are threatened by the issues of power quality. Negative sequences due to network unbalance can harm generating and transmitting equipment [12]. High frequency harmonics are likely to cause damage to electrical equipment and accidents, particularly the higher order harmonics taken by the AC-DC-AC electric trains [13]. Reactive power can enhance line and devices failure, increases the power lines and transformers voltage drop and have adverse effects on the grid and equipment [14]. Researchers have suggested a number of schemes in response to problems of power quality [15]. The harmonics and reactive power problems were solved through a passive filter [16]. The static var compensator is employed to address the negative sequence currents (NSC) and reactive power control, but its ability to remove harmonics is relatively very small [17]. Static synchronous compensator (STATCOM) has improved harmonic characteristics and can be used for the compensation of NSC, harmonics and reactive power [18]. The active power filter is able to efficiently resolve issues of power quality [19]. However, the solutions are proposed only to deal with issues of power quality but are not intended to solve the neutral section issues. Some investigators have recently suggested co-phase power supply structures to address neutral problems and power quality simultaneously [20]. One type is the co-phase power supply compensation system, while the other is the advanced co-phase power-supply scheme [21]. The compensation systems will simultaneously solve the problems with power quality and the neutral section [22]. These co-phased power supply schemes using power controllers include China's first co-phase power supplier, operating in 2010 on Mershan traction substation and the first single co-phase power delivery unit in 2014 in the Shangyu traction substation, as well as the active power compensator and the railway power conditioner [23].

However, in terms of basic power supply mode, these power supply systems are not precisely explained. The fast trains are developing worldwide because of their speed, high capacity, minimum average energy consumption, slight ecological impacts and good financial profits attract great interest from many countries. Japan is first using AT power supply modes on high-speed trains to increase the traction network's power supply capability, minimize the substations quantity and the electromagnetic intervention to neighboring transmission conductors [24]. Only Germany installed a railway power grid at a frequency other than the utility grid, to exclude it from the public grid, complete the same process, cancel the neutral portion and implement the power supply system co-phased [25]. The advanced supply schemes using power converters can address power quality issues and remove all neutral sections of the traction system simultaneously. These power supply methods can be broken down into compensatory power supply systems and continuous supply schemes. Compensative power-supply co-phase schemes include joint power-supply systems. Continuous co phase supply schemes include continued joint phase power supply systems built on cascading half bridge design, continuous, multilevel modular supply schemes (MMC). The primary contribution of this research paper is that a new MMC based traction supply scheme with a DC link, which is meant to assure the regular performance of proposed system through control and modulation techniques. Neutral sections may fully be eliminated and problems of power quality may be comprehensively resolved in the proposed system. The technique of modulation using module voltage balance, MMC based rectifier control techniques and droop characteristics based control of inverters are developed in this work, which guarantee that the suggested system will function properly. In section 2, the proposed system structure is enlightened. Mathematical modelling and control of rectifier is discussed in section 3. Simulation and experimental setup is described in section 4 and finally the conclusions are précised in section 5.

2. PROPOSED TRACTION SUBSTATION POWER SUPPLY STRUCTURE

The proposed three phase to single phase power transmitting scheme can address neutral section problems and power quality concerns simultaneously and effectively. The compensatory power supply system is to be combined with the traction transformer to supply the power to rail network. A power electronic back-to-back structure used for the continuous co-phase system of power supply is directly connected to the traction network. It is possible to regulate the frequency and magnitude of the output voltage. The rail network will stretch the same phase across the whole catenary line and achieve a complete continuous power line. Simultaneously, the NSC, reactive power and harmonics can also be well compensated. In a novel co-phase power supply system, the traction transformer is replaced with a co-phase power supply unit, which usually consists of switching devices in back to back structures as shown in Figure 2, in the conventional power supply system that links the three-phase power grid and the traction network. The power quality problems can be solved on the three phase grid side by regulating the rectifier side structure. The phase, amplitude and the frequency of output voltage provided to the rail network are controlled to attain equal output voltage through out the co-phase traction network, thereby deleting the NS by monitoring the inverter side with the back to back structure. This enables the power supply to solve NS problems and power quality problems completely and simultaneously.

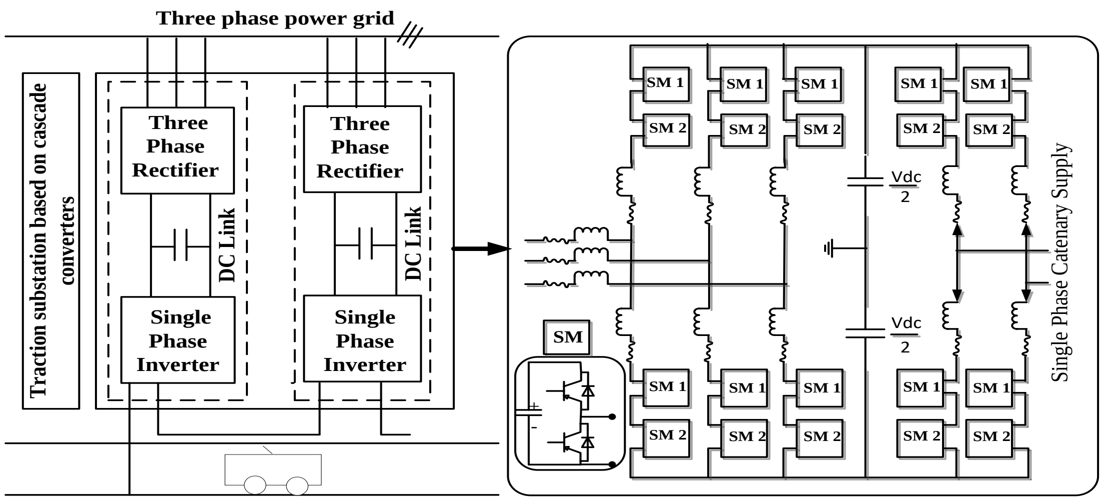


Figure 2. Three phase to single phase traction substation structure with MMC

Multilevel modular converters (MMC) are used in back-to-back traction substation structure. MMC structure is mainly divided into three parts, first one is the three phase rectifier and second one is the DC controller unit and finally the single phase inverter at output side. In this paper three modules in each arm have been taken for the simulation. The important simulation parameters are given in the Table 1.

Table 1. Simulation parameters of the suggested scheme

Important Parameter	Value
Primary & Secondary voltage of transformer	132kV/ 27.5kV
DC Capacitor	5400 µF
DC Voltage reference value	50kV
Phase modulation inductance	1.4 mH
Switching frequency	1000 Hz
Capacity	35 MVA
Output side smoothing inductor	7.2mH
Output voltage	27.5kV

3. DESIGN AND CONTROL OF THREE PHASE RECTIFIER AND INVERTER OUTPUT

The topology suggested in this paper is indeed a two way power flow design at the rectifier side, which consists of three legs and each leg consists of six modules (three modules are present in upper arm and remaining three are in lower arm) as mentioned in Figure 2. A three-phase MMC-based rectifier strategic approach and single-phase inverter controller design are included in the overall MMC control system of the proposed unconventional traction energy supply system. The MMC-based rectifier control strategy comprises of the DC voltage monitor and dual current loop control which maintain the stability of the DC voltage and guarantee the functioning of the unit power factor at the AC side. The single-phase MMC-based inverter in this study has a control technique of cascaded control with droop control method.

3.1. Modelling and control at there phase rectifier side

The control strategy must be encountered as a co-phase traction system in accordance with the operating principle of proposed traction system on the rectifier side at the same moment. The main principle is to prevent PQ problems initiated by the traction system and the DC link voltage should be alleviated close to the reference value at the same time. The control targets of controllable amplitude and output voltage must be achieved on the inverter side in order to maintain the voltage of the equal amplitude and phase in all the substations of the rail network. Furthermore, a voltage of 27.5 kV, single phase AC voltage is required for the connection between the network and the rail.

According to the block diagram shown in Figure 3, applying circuits laws the fallowing (1a) and (1b) can be depicted as:

$$V_{sj} = -L\frac{di_u}{dt} - V_{uj} - V_{NO} - \frac{1}{2}V_{dc}, (j = a, b, c) \tag{1a}$$

$$V_{sj} = -L\frac{di_l}{dt} - V_{lj} - V_{NO} - \frac{1}{2}V_{dc}, (j = a, b, c) \tag{1b}$$

$L = L_s + L_o$, R_0 is so insignificant that can be overlooked. Make $V_{NO} = 0$ adding and subtracting above two equations from each other, the results obtained as:

$$V_{sj} = \frac{L}{2}\frac{d(i_{lj} - i_{uj})}{dt} - \frac{1}{2}(V_{li} - V_{ui});\ (j = a, b, c) \tag{2a}$$

$$V_{sj} = L\frac{d(i_{lj} + i_{uj})}{dt} + (V_{li} + V_{ui}); (j = a, b, c) \tag{2b}$$

where, i_s - source current, i_c - Circulating current, i_u- Upper arm current, i_l- Lower arm current.

$$i_s = i_l - i_u \tag{3a}$$

$$i_c = \frac{i_u + i_l}{2} \tag{3b}$$

The mathematical relation among them as (4).

$$i_{u,l} = -\frac{i_s}{2} + i_c \tag{4}$$

As per the instant power, the rectifier side as examined, and the consequences as fallows:

$$P_{au} = u_{au} i_{au} \tag{5a}$$

$$P_{al} = u_{al} i_{al}. \tag{5b}$$

Overlooking the harmonic contents results the bridge arm's current and voltage expression as fallows:

$$U_{au,al} = \frac{1}{2}u_{dc} \pm \sqrt{2}V_a \sin \omega\, t. \quad (6)$$

$$I_{au,al} = \pm\frac{1}{2}\sqrt{2}I_a \sin(\omega t + \varphi) - \frac{1}{3}I_{dc} \quad (7)$$

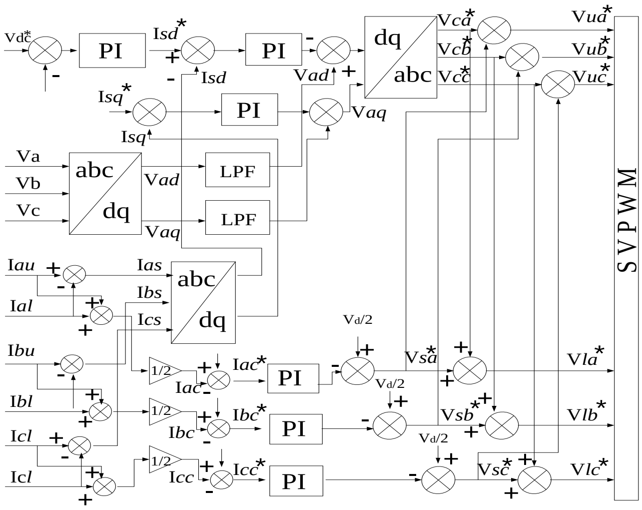


Figure 3. Control block diagram of the three phase rectifier

3.2. Single phase inverter control (droop characteristics)

The single phase inverter structure and droop control characteristics are illustrated in Figure 4. The LC filter is used to reduce the noise switching in high frequencies. The actual and reactive power are computed to eliminate any high-frequency signal before the measured voltage and frequency are compared to the reference values as the input for the break control synchronization with another inverter. The PI controller generates the reference current and this produced power is then supplied to the voltage point by additional PI controller. The inverter output is combined by a coupling inductor. A damping resistor R_d is employed at resonant frequency to prevent instability. PLL is used to coordinate the frequency with a direct axis based on the d-q technique. The orthogonal transformation takes place with the PLL phase angle. Each inverter has its own local reference frame. While a global referral framework is available that is the inverter 1 reference, the other inverter 2 must transform its confined orientation to a universal orientation.

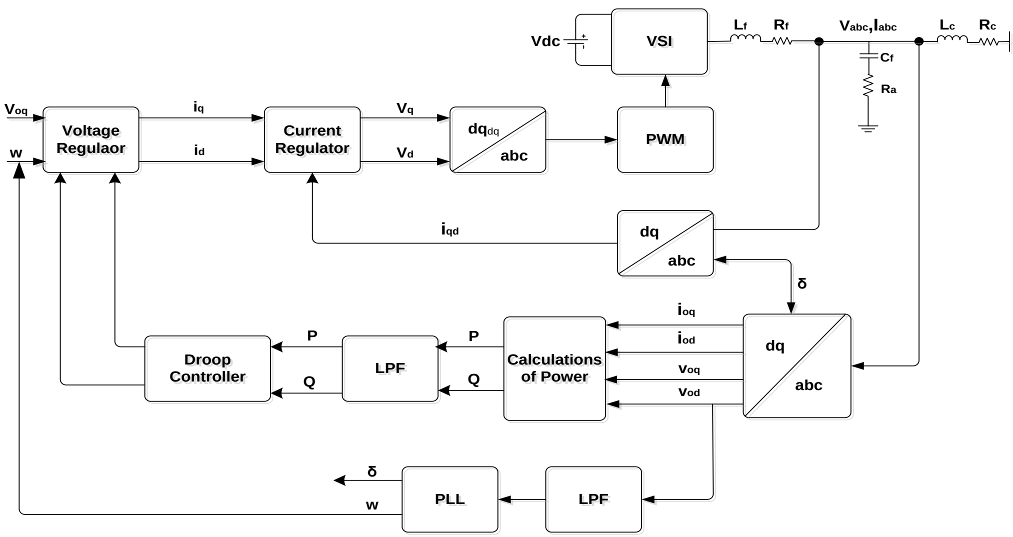
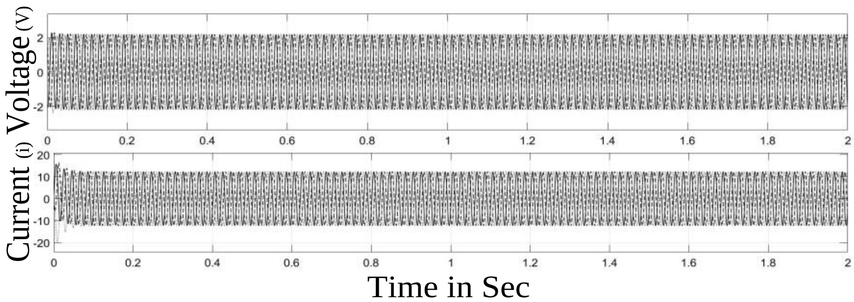


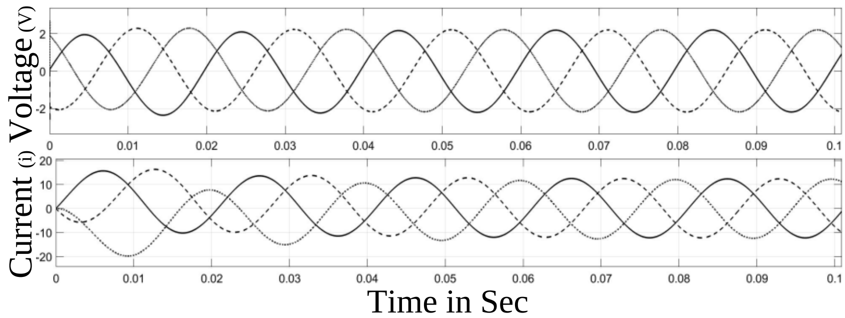
Figure 4. Line diagram of droop control method for self-synchronization of two parallel inverters

4. SIMULATION AND EXPERIMENTAL RESULTS

In this segment, simulation drafts the operational method of the suggested topology. A practical AC-DC-AC substation model is constructed. The input power grid voltage is taken as 132 kV. A step-down transformer is used to pass the lowered voltage from three phase grid to the to the AC grid of the substation. Then attach the secondary side to the back to back MMC converter. The rated phase voltage is maintained as 27.5 kV on the output side. The proposed co-phase power-supply needs to perform the following functionalities to achieve the objectives. In order to prevent power problems in the power grid, the rectifying side should eliminate NSC, reactive current, harmonics and stabilize the DC bus voltage. As on the inverter side, the amplitude and phase of the output voltage must be regulated at the reference value of the control. The voltage and current on the rectifier side essentially do not have a phase gap, meaning that their power factor is essentially one. The voltage and current results have a steady width and decent waveforms with no NSC and harmonic elements, which meet the power supply system functional specifications on the three phase rectifier side is mentioned in Figure 5(a). The Figure 5(b) shows that the DC bus voltage can be increased by the minimum voltage and stabilized at the reference value, fulfilling the DC bus voltage requirements. The magnitude and phase of the voltage can be alleviated at the reference value on the output side, and to check that the voltage stays stable and practically unchanged when the current shifts abruptly. The mutation of the load is 0.5 s, which immediately shifts the current. The voltage is constant and essentially unchanged, it can be seen from Figure 6(a). The inverter side will also satisfy the functional needs of the power supply system. In summary, it’s confirmed that the whole system is able to satisfy the system requirements of the power supply for co-phase system scheme. Five level traction substation output voltage is shown in Figure 6(b), which indicate clearly that if the number of modules increases then the output waveform is seamlessly sinusoidal in nature.



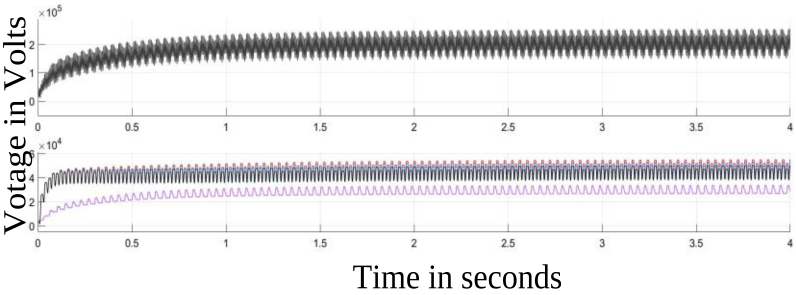
(a)



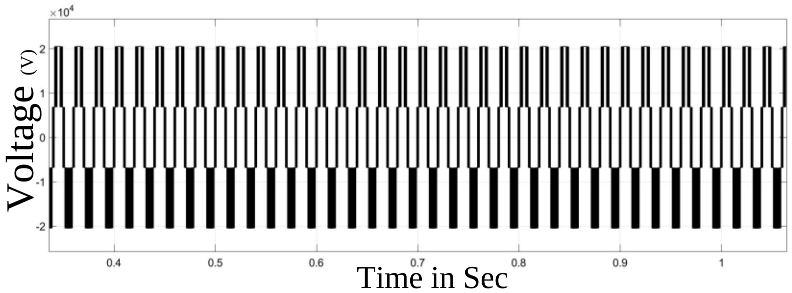
(b)

Figure 5. Three phase input side voltage and current waveforms: (a) without zoom, and (b) with zoomed output

A low voltage prototype compared to practical traction system is built to further validate the proposed new MMC traction power supply and the prototype is represented in Figure 7. It consists of a three-phase MMC rectifier, two traction substations and a DSP primarily control system. Here the hardware implementation of MMC for a single phase with the DSP controller is implemented and the programing to the converter is done using the embedded coder in MATLAB. The procedure with circuit and outputs are explained in this section. Two parallel inverters are connected and synchronized with the droop control characteristics. The individual sub modules are fed by the pulses are generated by DSP. MOSET switches are operated and controlled with pulses as described previously. Pulses are inverted before sent to the controller as upper and lower arm modules have to be operated in n different mode. The LC section of a filter's inductance and capacitance parameters can be adjusted to the frequency at which system harmonics are focused mainly to reduce operating voltage. The traction load harmonics, for example, are mostly concentrated in the third harmonics according to prior studies. This work is therefore tuned to the third harmonics of the inverter phase combined with LC values.



(a)

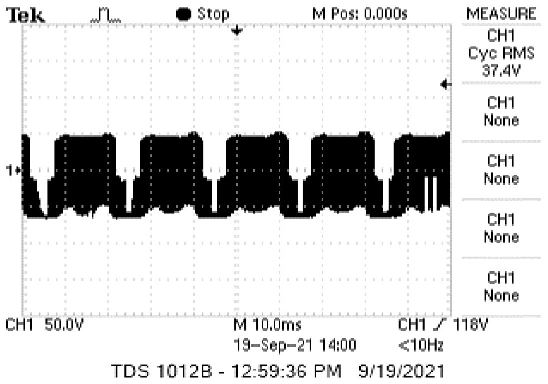


(b)

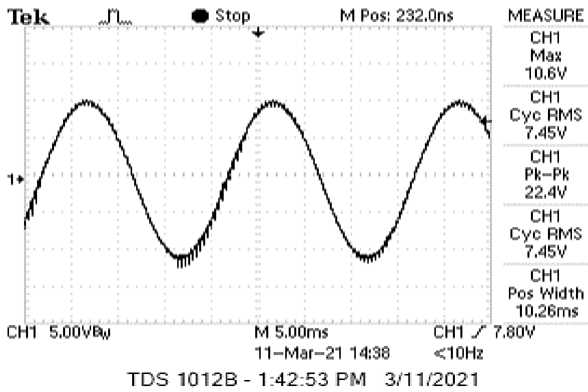
Figure 6. Simulation output voltage waveforms: (a) DC-link voltage, and (b) single phase inverter voltage

Figure 7. Experimental setup picture

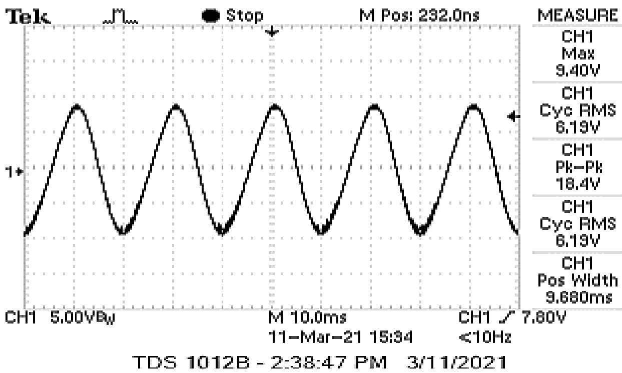
A low pass filter is added after the real and reactive power is calculated to remove any unwanted high frequency signal before it is given as input to the droop controller synchronization with other inverter. The reference current is generated from the PI controller. This generated current is then input to another PI controllers to generate the voltage reference. A coupling inductor is used to couple the inverter output. At resonant frequency to avoid instability a damping resistor (R_d) is used. PLL based on the dq method is used to synchronize the frequency with direct axis. Each inverter is synchronized to its own local frame of reference. The single phase inverter output voltage waveprm is shown in Figure 8(a) through the filter. Droop control techique is used along with the LC filter to synchronise the two inverters of successive traction substations and the results are dipicted in the Figure 8(b). The magnitude and phase of the output voltage of the two traction substations are identical which shows that the proposed droop control is suitable for proposed high speed traction supply system the synchronized output voltage with droop control is shown in Figure 8(c).



(a)



(b)



(c)

Figure 8. Inverter output voltage: (a) with out filter, (b) with filter, and (c) with droop control characteristics

5. CONCLUSION

This paper has discussed an improved traction power supply system based on MMC converter, which is predicted to be remove all the neutral portions in the standard traction energy system and alleviate power quality problems. The possible solutions for improving power quality in Indian railways are mentioned and suitable strategy implemented in this paper. MMC based rectifier and inverter systems are developed for control and effective traction operation. Experimental findings shows that the voltage of the module capacitor is balanced. Uniform power factor operation and DC voltage stabilisation may be maintained by the rectifier under the strategic double current-loop control with the DC voltage control. Dual closed loop controls are developed for the inverters combined with the droop control and the circulating current in the system is suppressed to ensure the standard operation of parallel traction substations. Prediction and dynamic load sharing among the parallel inverters in traction substations is the scope of the praposed system.

REFERENCES

[1] R. Li, H. Lin, C. Cai, L. Zhu, H. Yan, and Z. Shu, "Voltage Balancing and High-efficiency Power Transmisson Technologies for A Power Electronic Traction Transformer," 2019 *22nd International Conference on Electrical Machines and Systems (ICEMS)*, 2019, pp. 1-4, doi: 10.1109/ICEMS.2019.8922078.

[2] Y. Ying, Q. Liu, M. Wu, and Y. Zhai, "The Flexible Smart Traction Power Supply System and Its Hierarchical Energy Management Strategy," in *IEEE Access*, vol. 9, pp. 64127-64141, 2021, doi: 10.1109/ACCESS.2021.3075768.

[3] R. Pramanik and B. B. Pati,"Modelling and control of a non-isolated half-bridge bidirectional DC-DC converter with an energy management topology applicable with EV/HEV," *Journal of King Saud University - Engineering Sciences, 2021,* doi: 10.1016/j.jksues.2021.03.004.

[4] K. Valeriy, S. Viktor, H. Petro, S. Myamlin, K. Yevhen, and L. Vitalij, "Hybrid railway traction power supply system," 2020 *IEEE 4th International Conference on Intelligent Energy and Power Systems (IEPS)*, 2020, pp. 208-211, doi: 10.1109/IEPS51250.2020.9263194.

[5] L. Liu, N. Dai, K. W. Lao, and W. Hua, "A Co-Phase Traction Power Supply System Based on Asymmetric Three-Leg Hybrid Power Quality Conditioner," in *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 14645-14656, Dec. 2020, doi: 10.1109/TVT.2020.3032939.

[6] Y. N. Vijaykumar, V. Vemulapati, N. Visali, and K. Raju, "Railway Power Supply System using Modular Multilevel Converter with Droop Characteristics," 2020 *4th International Conference on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore*, 2020, pp. 12-20, doi: 10.1109/ICECA49313.2020.9297599.

[7] Q. Wang, S. Lin, T. Li, and Z. He, "Intelligent Proactive Maintenance System for High-Speed Railway Traction Power Supply System," in *IEEE Transactions on Industrial Informatics*, vol. 16, no. 11, pp. 6729-6739, Nov. 2020, doi: 10.1109/TII.2020.2974872.

[8] H. Hu, Z. He, X. Li, K. Wang, and S. Gao, "Power-Quality Impact Assessment for High-Speed Railway Associated With High-Speed Trains Using Train Timetable—Part I: Methodology and Modeling," in *IEEE Transactions on Power Delivery,* vol. 31, no. 2, pp. 693-703, April 2016, doi: 10.1109/TPWRD.2015.2472994.

[9] V. Vemulapati, Y. N. Vijayakumar, and N. Visali, "Droop Characteristics based High Speed Traction Power Supply system using Modular Multilevel Converter," 2020 *4th International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli,* India, 2020, pp. 111-118, doi: 10.1109/ICOEI48184.2020.9142920.

[10] S. J. Alam and S. R. Arya, "Control of UPQC based on steady state linear Kalman filter for compensation of power quality problems," in *Chinese Journal of Electrical Engineering*, vol. 6, no. 2, pp. 52-65, June 2020, doi: 10.23919/CJEE.2020.000011.

[11] M. Chen, Q. Chen, W. Sheng, and C. Zheng, "Research on DC bus voltage ripple and circuit degradation of 3L-NPC inverters," 2019 *14th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, 2019, pp. 799-803, doi: 10.1109/ICIEA.2019.8834188.

[12] V. Vemulapati and S. L. Devi, "Laboratory Prototype Model of a High Speed Railway Supply System for Performance Enhancement with Multi Module Converter in Indian Railways," 2021, doi: 10.2139/ssrn.3852693. Available at SSRN: https://ssrn.com/abstract=3852693 or

[13] J. L. Torre, L. A. M. Barros, J. L. Afonso, and J. G. Pinto, "Development of a Proposed Single-Phase Series Active Power Filter without External Power Sources," 2019 *International Conference on Smart Energy Systems and Technologies (SEST),* 2019, pp. 1-6, doi: 10.1109/SEST.2019.8849010.

[14] X. Sun, R. Han, H. Shen, B. Wang, Z. Lu, and Z. Chen, "A Double-Resistive Active Power Filter System to Attenuate Harmonic Voltages of a Radial Power Distribution Feeder," in *IEEE Transactions on Power Electronics*, vol. 31, no. 9, pp. 6203-6216, Sept. 2016, doi: 10.1109/TPEL.2015.2500913.

[15] X. Zhu and B. Wang, "The power quality analysis of traction power supply system," *Proceedings of the 33rd Chinese Control Conference,* 2014, pp. 6313-6318, doi: 10.1109/ChiCC.2014.6896027.

[16] D. Xiao, M. Chen, and Y. Chen, "Negative sequence current and reactive power comprehensive compensation for freight railway considering the impact of DFIGs," in *CPSS Transactions on Power Electronics and Applications*, vol. 6, no. 3, pp. 235-241, Sept. 2021, doi: 10.24295/CPSSTPEA.2021.00022.

[17] M. Chen, J. Luo, W. Jiang, and Y. Wang, "Study on new traction power supply system for power quality comprehensive compensation in electrified railway," *TENCON 2015 - 2015 IEEE Region 10 Conference,* 2015, pp. 1-5, doi: 10.1109/TENCON.2015.7372869.

[18] H. V. Nguyen and D. Lee, "Comparison of power losses in single-phase to three-phase AC/DC/AC PWM converters," 2015 *9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia),* 2015, pp. 940-945, doi: 10.1109/ICPE.2015.7167894.

[19] M. Li *et al.,* "Four-Port Modular Multilevel AC/AC Converter in Continuous Co-phase Traction Power Supply Application," *2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020*, pp. 1477-1481, doi: 10.1109/ECCE44975.2020.9236132.

[20] Y. Zhao, N. Y. Dai, and B. An, "Application of three-phase modular multilevel converter (MMC) in co-phase traction power supply system," *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific),* 2014, pp. 1-6, doi: 10.1109/ITEC-AP.2014.6941064.

[21] B. Purkayastha and T. Bhattacharya, "Submodule Capacitor Voltage Regulation of Modular Multilevel Converter Based Traction Propulsion System With Medium Frequency Isolation," in *IEEE Transactions on Industry Applications,* vol. 57, no. 1, pp. 904-914, Jan.-Feb. 2021, doi: 10.1109/TIA.2020.3036327.

[22] X. He *et al.,* "Advanced Traction Power Supply System Based on Modular Multilevel Converters," *2018 Asian Conference on Energy, Power and Transportation Electrification (ACEPT),* 2018, pp. 1-8, doi: 10.1109/ACEPT.2018.8610818.

[23] B. Li, J. Hu, S. Zhou, and D. Xu, "Hybrid back-to-back MMC system for variable speed AC machine drives," in *CPSS Transactions on Power Electronics and Applications*, vol. 5, no. 2, pp. 114-125, June 2020, doi: 10.24295/CPSSTPEA.2020.00010.

[24] S. N. Duarte, B. C. de Souza, P. M. de Almeida, L. R. de Araújo, and P. G. Barbosa, "A Compensation Strategy Based on Consumer's Voltage Unbalance Assessment for a Distribution Static Synchronous Compensator," *in IEEE Latin America Transactions,* vol. 18, no. 01, pp. 156-164, January 2020, doi: 10.1109/TLA.2020.9049473.

[25] X. He, H. Ren, P. Han, Y. Chen, Z. Shu, and X. He, "Open Circuit Fault Diagnosis of Advanced Cophase Traction Power Supply System Based on Neural Network," *2018 International Conference on Intelligent Rail Transportation (ICIRT),* 2018, pp. 1-5, doi: 10.1109/ICIRT.2018.8641605.

BIOGRAPHIES OF AUTHORS

Venkatasupura Vemulapati born in 1989 in India and received his B.Tech degree in Electrical and Electronics Engineering from K L University (Formerly KLCE), Guntur, India in 2010 and M.Tech degree from JNTUA College of Engineering, Anantapur, India in 2012. Currently he is pursuing Ph.D in JNTUA College of Engineering, Anantapur, India. His research interests include power electronics and drives, Power quality and railway power supply systems. He can be contacted at email: vvsupura@svcolleges.edu.in.

Dr. Yerram N. Vijaykumar received his Ph.D. in Electrical Engineering from JNTUA College of Engineering, Kakinada, India in 2016. He is currently working as a professor & head of the electrical and electronics engineering department at Sri Venkateswara College of Engineering & Technology (A), Chittoor, India. His research interests include power electronic converters, control engineering and power quality analysis in power system. He may be contacted at email: yn.vijaykumar@gmail.com.

Dr. Nagalamadaka Visali received her Ph.D degree from JNTUA College of engineering, Ananthapur, India in 2013. Presently she is working as a Professor and head of the Electrical & Electronics Engineering department, JNTUA College of Engineering, Ananthapur, India. She has also published more than 50papers in reputed journals and IEEE conerences. Her research interests include Electrical distributing systems, FACTS devices and deregulated power systems. She may be contacted at email: nvisali@gmail.com.