Prototype Model for High Speed Railway Power Supply System Suitable for Indian Traction Sub Stations using Multi Modular Converter

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ABSTRACT

As on 2020, India does not have any globally proven railway lines running with high-speed standards as above 250 km/h. Indian Railways looking at the prospect of high speed rail networks also known as bullet rail network in India. With the present Indian traction supply system which is based on the phase splitting or phase shifting method is not suitable for the high speed railway network unless we eliminate neutral sections as well as mitigating the power quality issues such as voltage unbalance, harmonics and high reactive power drawn from the utility grid. In this paper, Co-phase traction power supply system with zero neutral sections is proposed. Modular multilevel converter based three phase to single phase catenary system through a DC Link has been designed, simulated and laboratory prototype is made. A MATLAB simulation of the suggested method and droop characteristics based on load sharing between the two single phase parallel inverters had executed. The obtained results were satisfactory and shows that the proposed system is very much suitable for high speed railway.

Keywords: Indian Railways, power quality issues in traction power supply systems, Traction sub stations, Neutral sections, Modular Multilevel Converter.

1. INTRODUCTION

Nowadays speed, reliability and standard power quality are the essential parameters in case of high speed railway [1]. Mainly the power supply system for locomotives has to be designed such a way that the system will satisfy the fore mentioned parameters. Many power transmission systems which are erected in various countries for traction network are presented in Figure 1. Indian Railway Traction substations receives an high voltage Three Phase 220/132/110 kV, 50 Hz power from local power generating stations and then the voltage is step down through a single-phase transformer [2]. To attain this, duplicate feeders containing only two phases are served from the supply authorities nearby grid to the traction substation as mentioned in Figure 1(b). This method is known as phase shifting or phase splitting method [3]. As the name itself indicates that, the supply phases are changes when the locomotive moves from one substation to another.

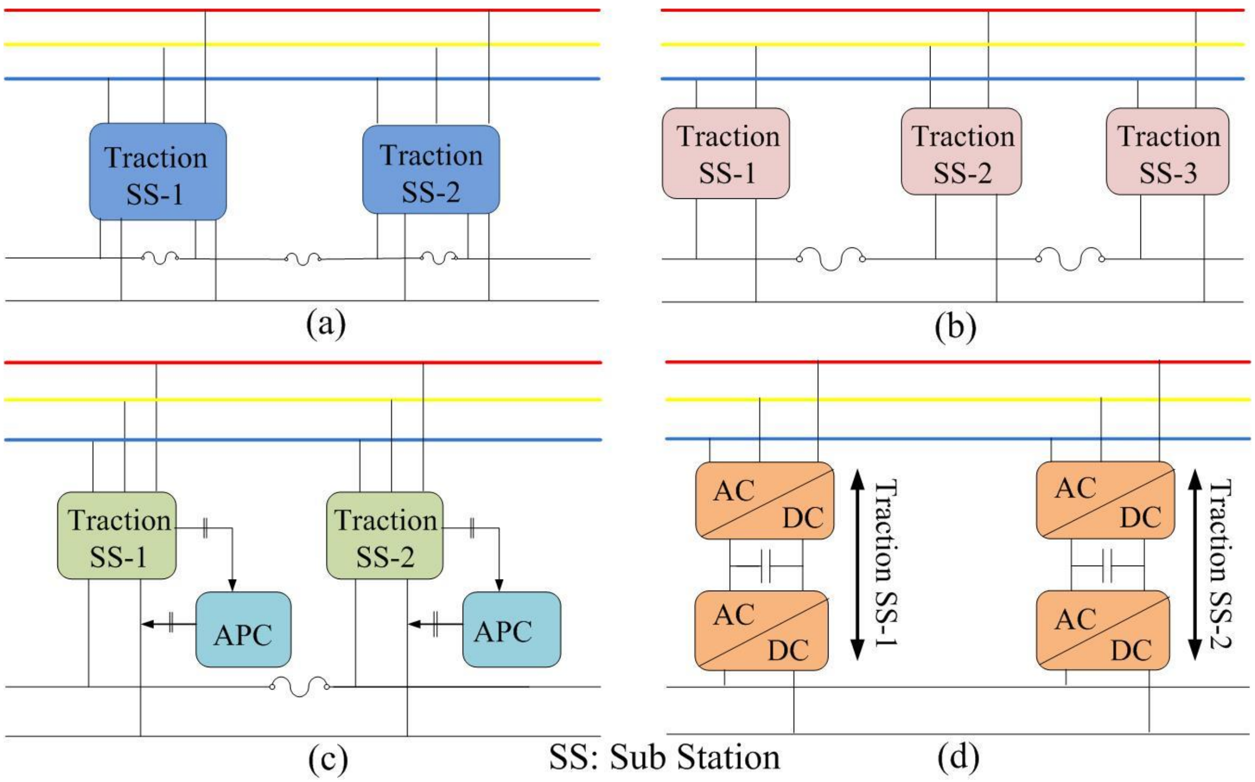


Figure 1. Several Traction Power Supply Systems with (a) Balanced Transformer (b) Phase Splitting Method (c) Railway Active power compensator (d) Co-phase Traction Method

Traction power supply stability depends on the sustaining traction voltage at feeding posts between 25kV and 27.5kV and a frequency between 48.5 and 51.5 Hz [4]. Locomotives working on AC supply will incorporate voltage unbalance, harmonic and reactive power issues in the traction network. The problems concerning power quality upswings when the load on traction network increases [5]. Moreover, neutral sections are necessary between substations especially in phase splitting network to avoid short circuit problems. The neutral section is described as a short isolated dead overhead device that usually separate contact wire fed by two adjacent traction substations [6]. During meeting on the neutral section, the locomotive is turned off to prevent flickering while it is leaving and re-entering the live area that leads to reduction of locomotive speed [7]. For an effective high-speed rail traction power supply the above mentioned problems must be solved.

There are many approaches to reduce the voltage unbalance Problems with the usage of balanced transformers such as Scott, YNvd, V/V connected transformers. But these solutions cannot adequately compensate for the issue of imbalance due to differences in traction load [8], [9]. Passive components such as condensers and filters can compensate for reactive power and harmonics [10]. Active compensators can have more complex and detailed coverage compared to passive compensators. Static VAR (SVC) and static synchronous compensator (STATCOM) are the most widely used traction compensators [11]. In [12] the performance of SVC output for 25-kV voltage control is explained. However, the results are not adequate when the load is dynamic in nature [13]. Hereby the Active Power compensators (APC) offered quick and vibrant response [14] but the system rating is too high [15]. A half bridge multilevel RPC converter is proposed in [16]. Co-phase traction power supply system is the newly developed traction power networks that will overcome the installation of neutral sections [17]. Removal of neutral parts will minimize the speed loss of locomotives [18], [19]. The use of advanced co-phase supply was then observed as a possible system that can solve the above problems [20].

2. THREE PHASE TO SINGLE PHASE MMC STRUCTURE

The simplified configuration of the traction substation based on MMC circuit is represented in the Figure 2. The DC-system of the MMC is sometimes referred to it as the DC-link, connected to the converter legs. The three-phase MMC rectifier is attached to the middle point of each leg. Each leg of the MMC shall be split into two arms [21]. The arms which are attached to the positive strip are refers as the upper arms (*u*), and the arms attached to the negative strip are known to as the lower arms (*l*). Each and every arm has a submodules (capacitor & switches) and an arm inductor (*L*) as shown in Figure. Arm inductor which is connected in series helps to limit circulating current caused due to the difference of voltage between each arm [22].

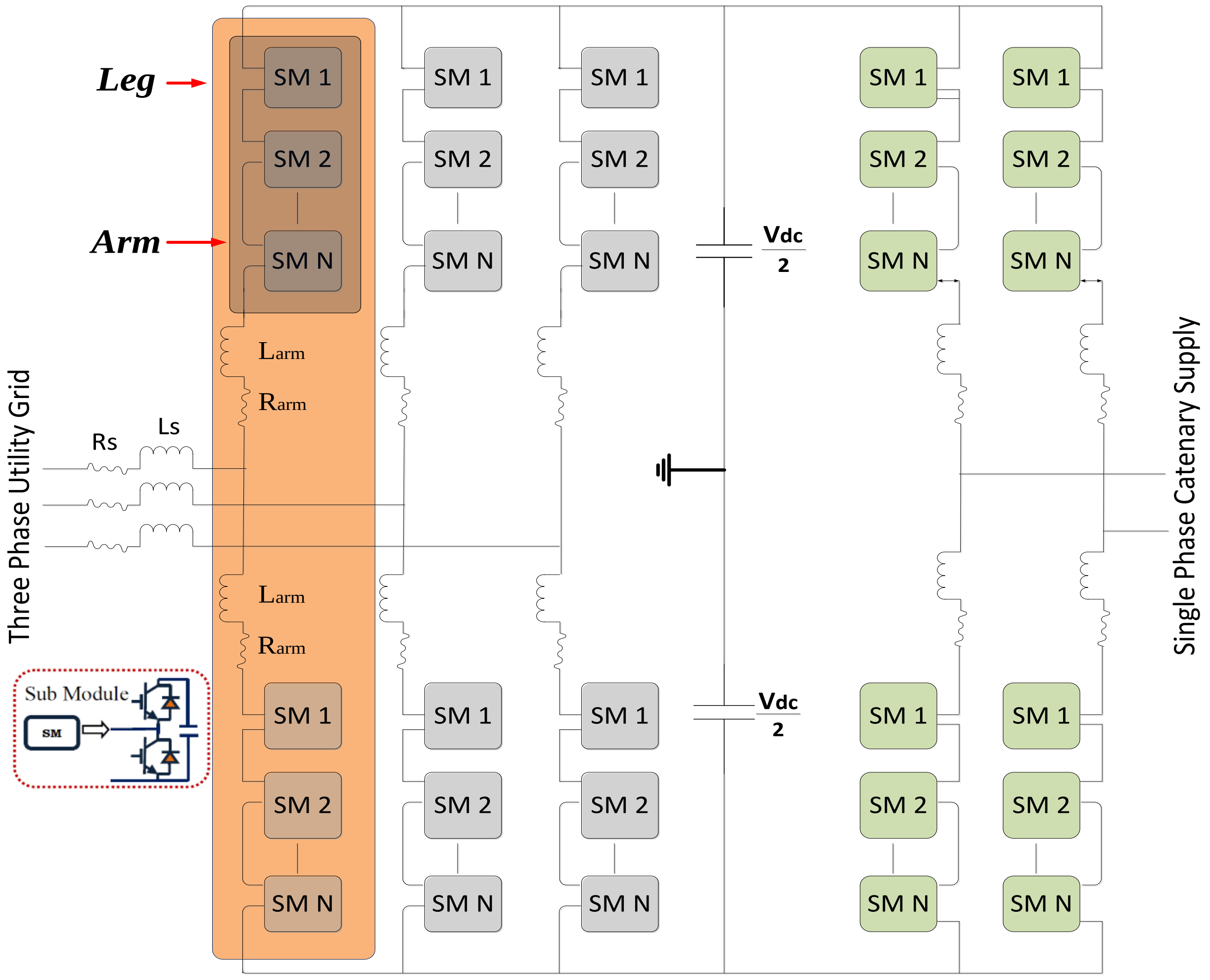


Figure 2. Three Phase to Single Phase MMC Converter with DC Link

The design of MMC based on half-bridge submodule connection is shown in Figure 2. It consists of two switches with antiparallel diodes (S1 and S2) and a single DC capacitor (C) [23]. The two IGBT devices are run in a complementary way in order to control voltage (V_c) across the capacitor and this voltage is specified as described in fallowing equation [24].

$$V_c = \frac{1}{C}\int_{0+}^{t} i_c\,(T)\,dT \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

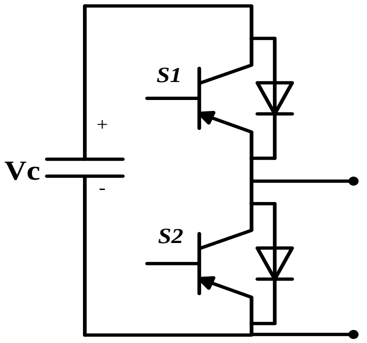


Figure 3. MMC Half Bridge sub module

3. MODELLING OF MULTI MODULAR CONVERTER

The scientific modelling of the MMC having three-phase rectifier (grid side) and single phase inverter (locomotive side) is described below. The Figure 2 shows the MMC converter on rectified side designed with half bridge submodules. Power loss in each arm is represented by an external arm resistor R_{arm}.

The Phase-a upper and lower arm current values cam be evaluated by the equations 2 (a) & 2 (b)

$$i_{u,a} = \frac{i_{dc}}{3} + i_{circ,a} - \frac{i_a}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2a)$$

$$i_{l,a} = \frac{i_{dc}}{3} + i_{circ,a} - \frac{i_a}{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2b)$$

Where $i_{u,a}$ − upper arm currents

$i_{l,a}$ − Lower arm currents,

$i_{circ,a}$ − Circulating current of the corresponding phase.

From the above equations 1(a) & 1(b) circulating current in phase-a can be calculated by substituting i_a &i_{dc}. Where i_a is the phase current and i_{dc} is the DC –Link voltage respectively.

$$i_{cir,a} = \frac{i_{u,a}+i_{l,a}}{2} - \frac{i_{dc}}{3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The dynamic behavior of the any phase in MMC can be regulated by the fallowing mathematical equations

$$\frac{V_{dc}}{2} - v_{u,a} = L_{arm}\frac{di_{u,a}}{dt} + R_{arm}i_{u,a} + v_a + v_{cm} \cdots \quad (4a)$$

$$\frac{V_{dc}}{2} - v_{l,a} = L_{arm}\frac{di_{l,a}}{dt} + R_{arm}i_{l,a} - v_a - v_{cm} \ldots \quad (4b)$$

Here,

$v_{l,a}$ − *phase 'a' module voltage of the lower arm.*

$v_{u,j}$ − *phase'a' module voltage of the upper arm.*

v_{cm} − *common mode voltage componant.*

v_a − *fundamental voltage component.*

The individual phase voltages of each arm can be calculated by subtracting equation 5 (b) from Equation 5 (a) and finally substituting upper arm and lower arm currents ($i_{u,a}$, $i_{l,a}$).

$$v_a + v_{cm} = \frac{v_{u,a} - v_{l,a}}{2} - \frac{R_{arm}}{2}i_a - \frac{L_{arm}}{2}\frac{di_a}{dt} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Add equations 4(a) and 4 (b) and finally substitute phase-a circulating current $i_{cir,a}$ then the obtained dynamic equation is represented in equation (6).

$$L_{arm}\frac{di_{cir,a}}{dt}+R_{arm}i_{cir,a}=\frac{V_{dc}}{2}-\frac{v_{u,a}-v_{l,a}}{2}-R_{arm}\frac{i_{dc}}{2}\dots\dots\dots\text{(6)}$$

The upper arm and lower arm phase $-\ a$ submodule voltages are represented by

$$v_{u,a}=n_{u,a}v_{cu,a}\dots\dots\dots\dots\dots\dots\dots\dots\text{(7a)}$$

$$v_{l,a}=n_{l,a}v_{cl,a}\dots\dots\dots\dots\dots\dots\dots\dots\dots\text{(7b)}$$

Where $v_{cu,a}$ $-$ The upper arm phase $'\mathrm{a}'$ individual submodule voltage
$\mathrm{v_{cl,a}}$ $-$ The lower arm phase $-$ a individual submodule voltage
DC link voltage is balanced by active capacitor controlled method.

$$v_a+v_{cm}=\frac{n_{l,a}v_{cl,a}-n_{u,a}v_{cu,a}}{2}-\frac{R_{arm}}{2}i_a-\frac{L_{arm}}{2}\frac{di_a}{dt}\dots\dots\dots\dots\dots\dots\text{(8)}$$

$$L_{arm}\frac{di_{cir,a}}{dt}+R_{arm}i_{cir,a}=\frac{V_{dc}}{2}-\frac{n_{l,a}v_{cl,a}-n_{u,a}v_{cu,a}}{2}-R_{arm}\frac{i_{dc}}{3}\dots\dots\text{(9)}$$

Furthermore,

$$P_{dc}=P_{ac}+P_{loss}\dots\dots\dots\dots\dots\text{(10a)}$$

$$V_{dc}I_{dc}=\sum\nolimits_{a=r,y,b}V_aI_a+P_{loss}\dots\dots\dots\dots\dots\text{(10b)}$$

$$P_{u,a}=v_{u,a}i_{u,a}=n_{u,a}v_{cu,a}i_{u,a}\dots\dots\dots\dots\dots\text{(11a)}$$

$$P_{l,a}=v_{l,a}i_{l,a}=n_{l,a}v_{cl,a}i_{l,a}\dots\dots\dots\dots\dots\text{(11b)}$$

The dynamic power equations for each arm can be represented by

$$P_{u,a}=\frac{dW_{u,a}}{dt}=\frac{d(\frac{N}{2}C_{SM}v_{cu,a}^2)}{dt}=v_{cu,a}NC_{SM}\ \frac{dv_{cu,a}}{dt}\dots\dots\dots\dots\dots\text{(12a)}$$

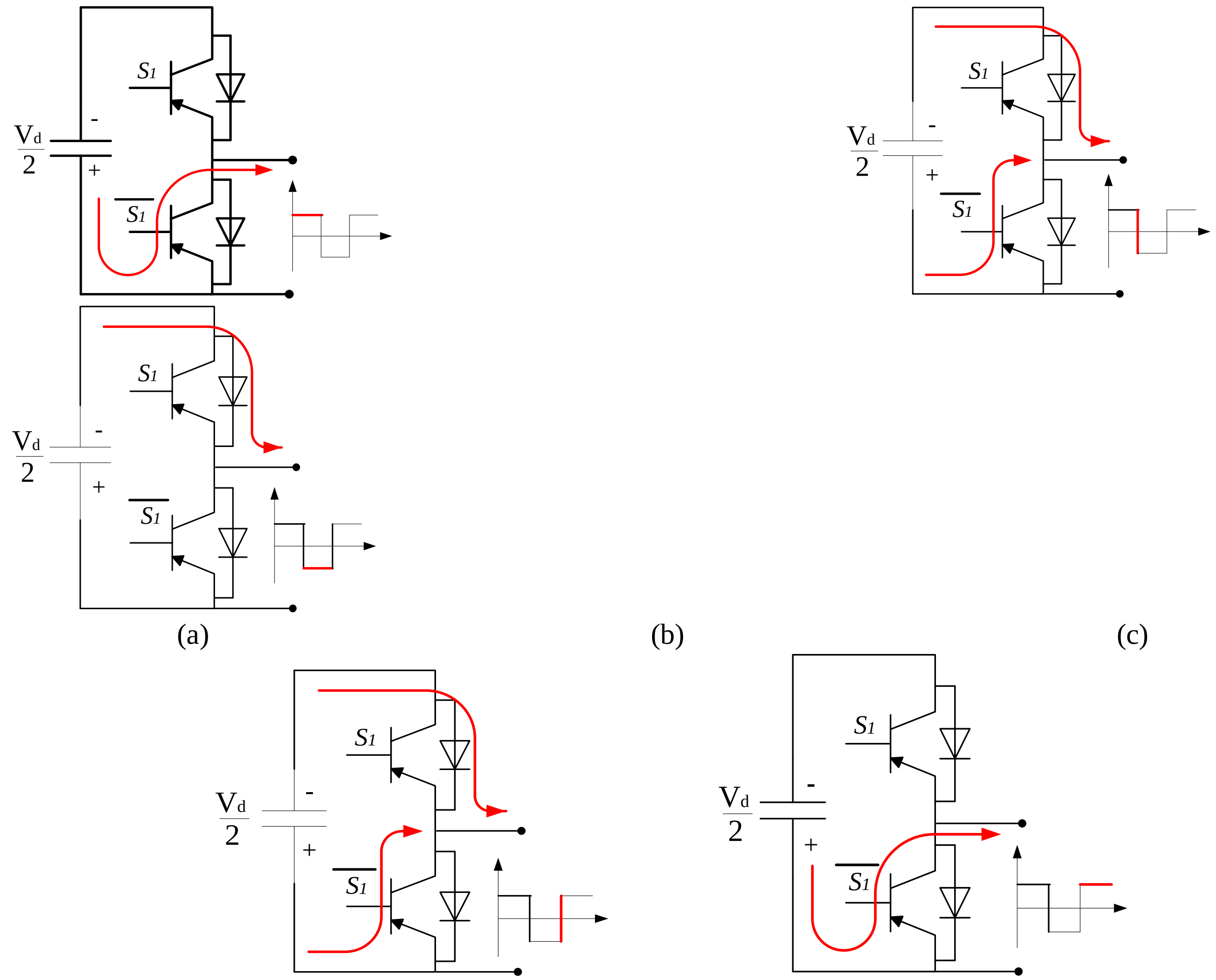
$$P_{l,a}=\frac{dW_{l,a}}{dt}=\frac{d(\frac{N}{2}C_{SM}v_{cl,a}^2)}{dt}=v_{cl,a}NC_{SM}\ \frac{dv_{cl,a}}{dt}\dots\dots\dots\dots\dots\text{(12b)}$$

Here C_{SM} $-$sub module capacitor value
The ripples in the power equations are evaluated by differentiating individual phase-a voltage with respect to time. The equations are given as

$$\frac{dv_{cp,a}}{dt}=\frac{i_{p,a}}{NC_{SM}}n_{p,a}=\frac{1}{NC_{SM}}\ (\frac{i_{dc}}{3}+i_{circ,a}+\frac{i_a}{2})n_{p,a}\dots\dots\dots\dots\dots\text{(13a)}$$

$$\frac{dv_{cn,a}}{dt}=\frac{i_{n,a}}{NC_{SM}}n_{n,a}=\frac{1}{NC_{SM}}\ (\frac{i_{dc}}{3}+i_{circ,a}+\frac{i_j}{2})n_{n,a}\dots\dots\dots\dots\dots\text{(13b)}$$

Inverter is operated and controlled independently by using droop control strategy as shown in the Figure 4. The single phase inverter output will be transferred to refuse the High Frequency (HF) switching with an LCL filter. The output of the LCL filter like voltage and current magnitudes are changed into *d-q* reference frame and these values are useful while calculating output power. The attained power is then passed through a low pass filter (LPF) and finally via droop controller components.



(a) (b) (c)

(d) (e)

Figure 4. Different switching operations of Singe Phase Inverter operation using half bridge MMC

4. SIMULATION AND EXPERIMENTAL RESULTS

To validate the operational characteristics of the system mentioned above, a five-level modular multilevel converter based on three-phase to single-phase simulation is carried out and laboratory experimental setup is developed. The important simulation and control parameters are given in Table 1.The reference voltage for locomotive is taken as 25kv and the simulation is run for 4s to understand the voltage and current profiles effectively.

Table 1. Simulation and Control parameters of proposed system

Parameters	**Values**
The utility grid voltage supply	132 kV
Rated Frequency	50 Hz
DC link voltage	40 kV
Traction load	100 Ω
Switching frequency	5 kHz.

Three phase Rectifier side inductance	~3mH
Single phase Inverter side inductance	~2mH
Simulation length	4.0s
Traction reference voltage	25 kV

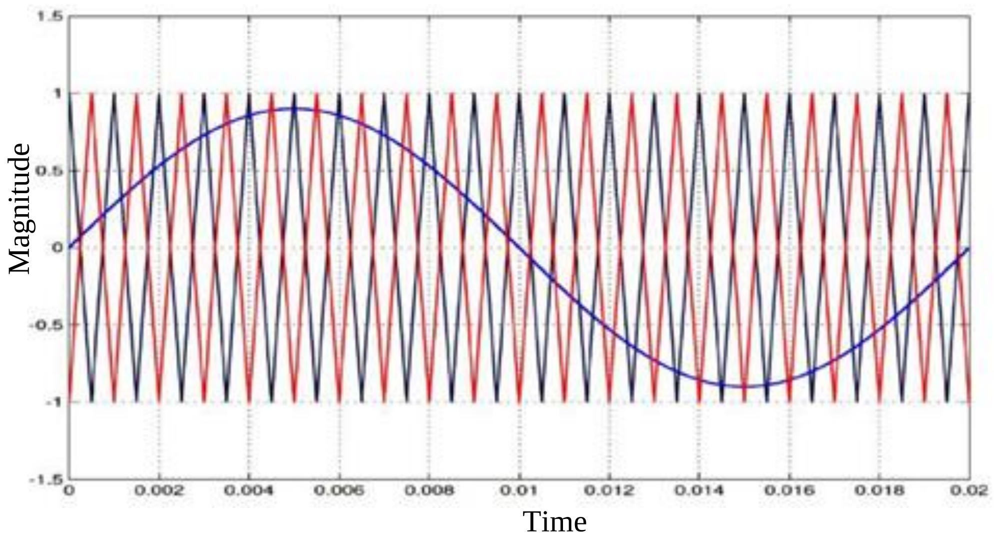


Figure 5. Phase shifted PWM generating waveform

4.1 **SIMULATION RESULTS:**

Sinusoidal Phase shifted PWM (SPS-PWM) technique is used for generating signals in this simulation. In this techniques phase of the carriers signals are shifted by an angle$\frac{360^0}{n}$, where 'n' indicates the no of modules per leg. Phase shifted PWM the most appropriate technique with minimal Total Harmonic Distortion (THD) for the MMC half-bridge network. Significant benefit of this technique compared to the phase-disposal techniques is that it leads to controlling the capacitors voltage since there is a movement of the modules activation embedded in the circuit which does not allow the overload or the high discharge of the individual modules. In the other hand, this dilemma can be seen in the methods of other PWM Methods.

. Three phase grid currents are mentioned in Figure 6. As the load is modelled by resistor, the power factor of the load is presumed nearly 1. The single phase traction voltage is displayed in Figure 7 and the wave form is of five level staircase under load condition. The single module voltage and DC link voltage of the MMC converter is shown in Figure 8, it is marked that the module capacitor voltage reaches to stable condition after 0.3s.

It can be found that the voltage wave, with decent sinusoidal wave shape, is a multilevel staircase. The further converters in the cascade structure, the narrower the filter circuit design specifications would be. When the cascade number is too high, thefilter circuit may be skipped to directly link the traction network. We can see that, to guarantee stable functioning, the load obtains a stable RMS voltage with a low THD (Total Harmonic Distortion) . When the current of the load is increased, the load voltage will decrease slightly, but it can be swiftly return to the reference value.

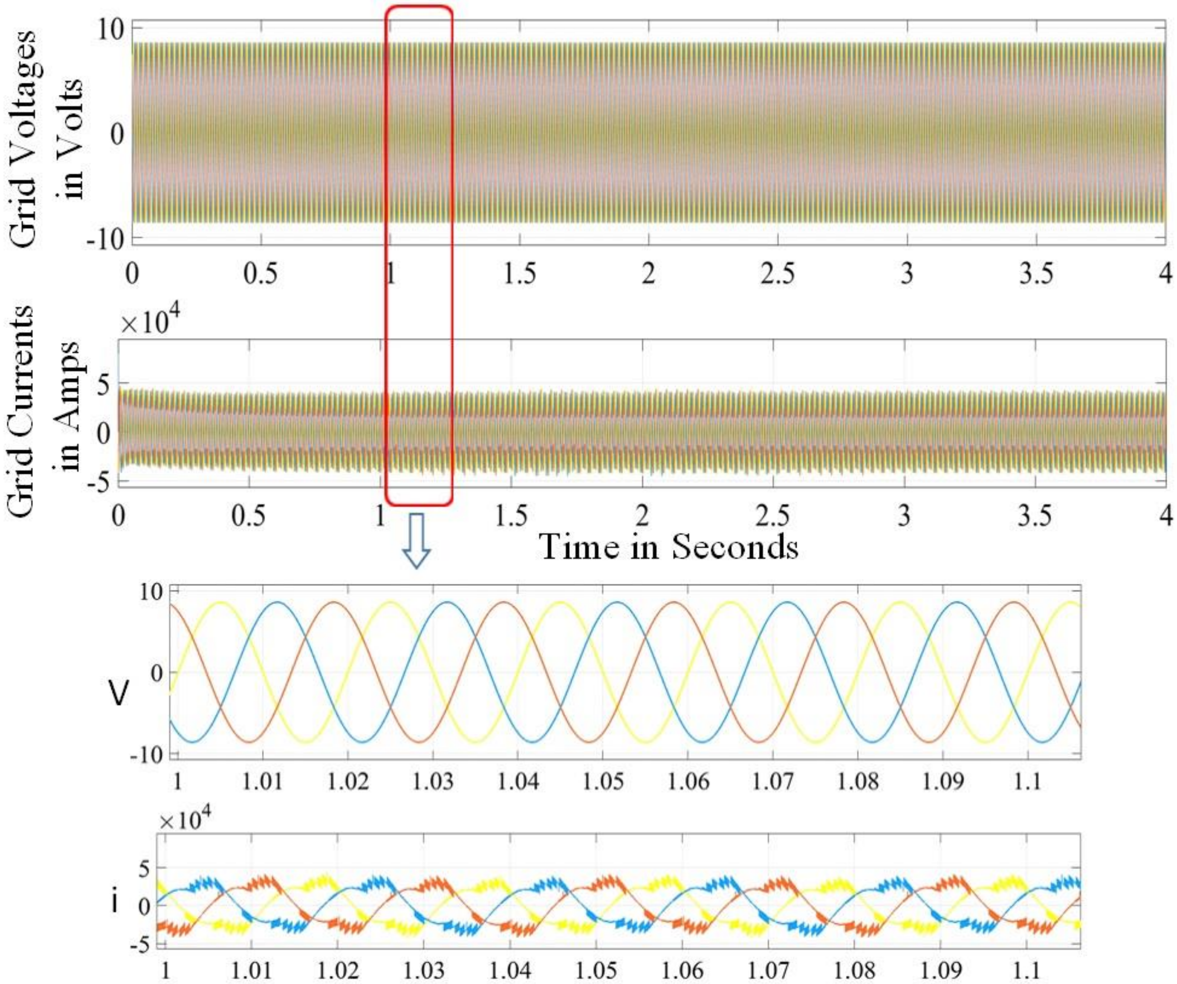


Figure 6. The Three phase grid voltage and current wave forms

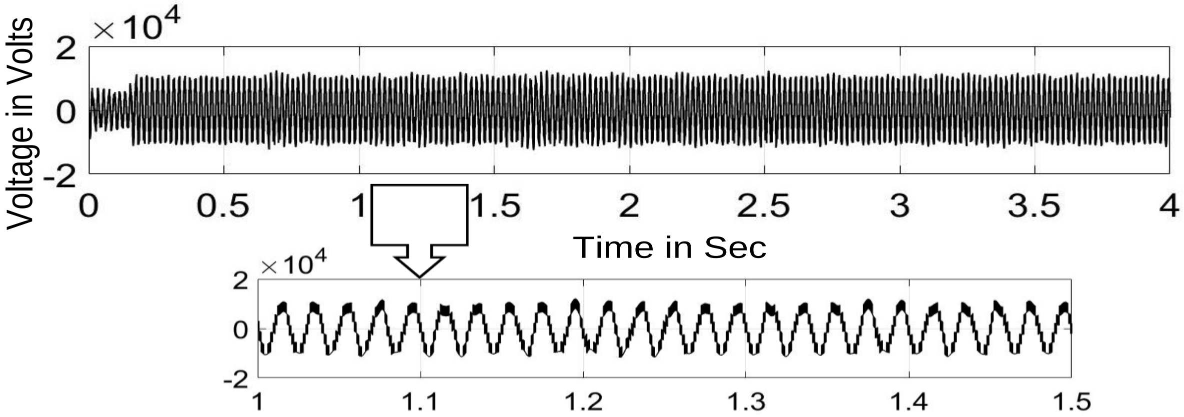


Figure 7. Five level single phase traction output (catenary) voltage waveform

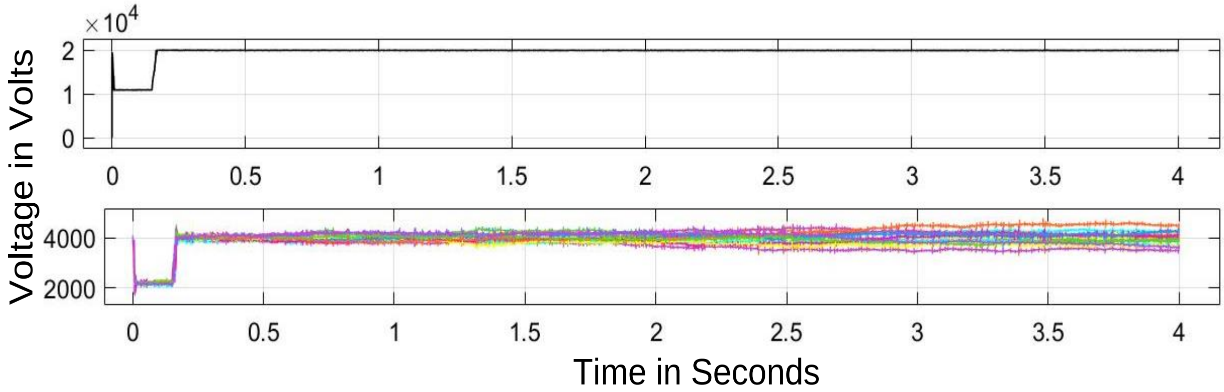


Figure 8. Single Module Voltage and DC Link Voltage of the MMC Converter

4.2 EXPERIMENTAL RESULTS

In order to verify simulation results, a low voltage experimental model has been developed as shown in Figure 9. To add the control device to an inverter built around an MOSET switch board, a Digital Signal Processor (DSP) was used. As a dc connection, a dc source was directly attached and the three phase inputs were connected to the rectifier. With a frequency of 5 kHz, space vector modulation was used as the switching scheme. The experimental findings gathered relate to the individual values that were logged in real time in the DSP. This was done by transmitting the necessary values over host system serial links. A schematic was given for the experimental setup in Figure 9.

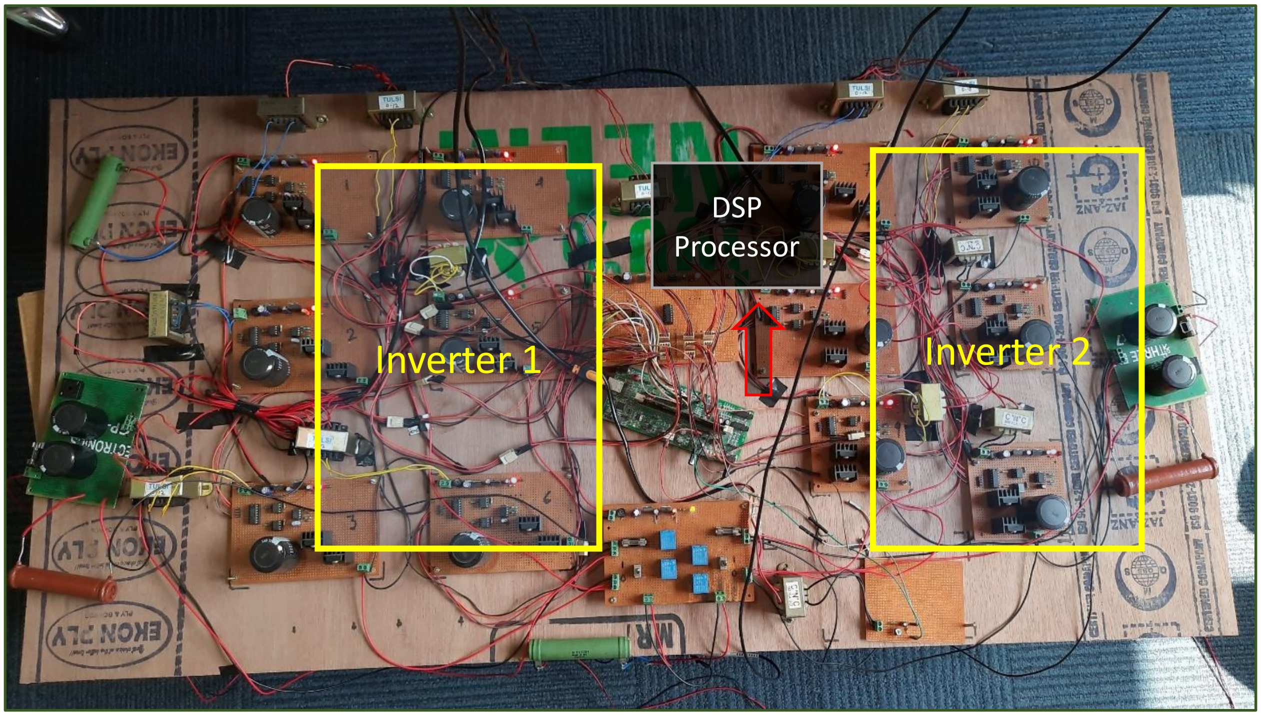
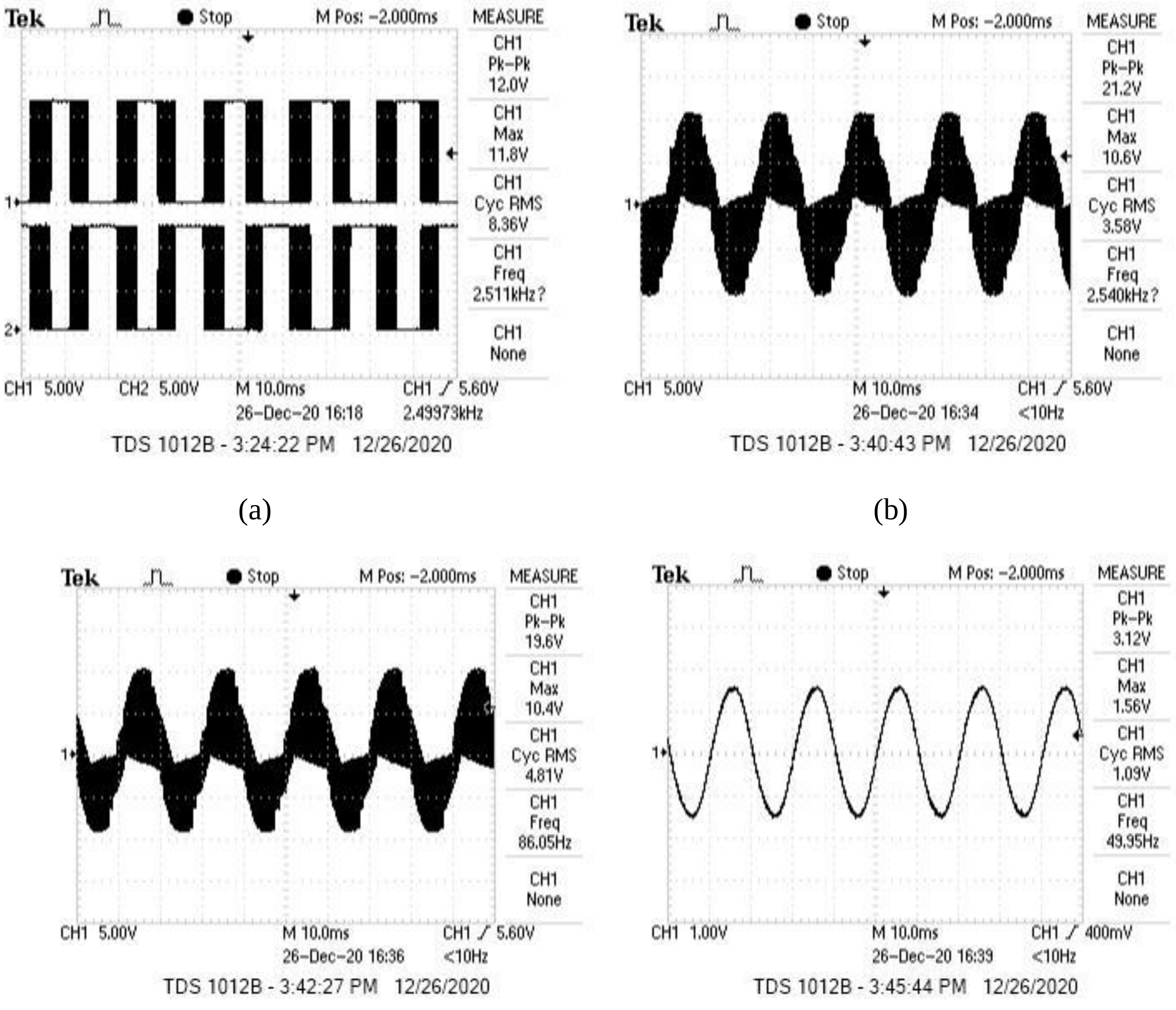


Figure 9. Low voltage experimental setup picture with two parallel inverters.

The experimental results are shown in Figure 10. Figure 10 (a) illustrate the module voltage of single phase inverter and the filtered output voltage of the catenary system is shown in Figure 10(d).All the experimental results are done in this paper for minimum voltage value. The operational performance of the system for higher voltages has to be done in further research



(a) (b)

(c) (d)

Figure 10. Laboratory prototype results (a) Single phase inverter side Module Volatge (b) Synchronized output voltage (c) individual single phase inverter voltage (d) Filtered output voltage of single phase output voltage

5. CONCLUSIONS

Traction supply system by means of multi modular converters with load balancing is discussed in this paper. Mathematical model and control method of MMC for rectifier and inverter are analysed. In addition, the droop characteristics of single phase parallel inverters related to two successive traction substations is discussed. Transformer can be removed at inverter side with the suggested MMC inverter. The variable traction load can be balanced with single phase drooping characteristics. The laboratory prototype results indicates that the basic operation and load sharing characteristics of proposed method is valid and reliable.The obtained results were satisfactory.

REFERENCES

[1] 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.

[2] N. Gunavardhini, M. Chandrasekaran, C. Sharmeela and K. Manohar, "A case study on Power Quality issues in the Indian Railway traction sub-station," 2013 7th International Conference on Intelligent Systems and Control (ISCO), Coimbatore, India, 2013, pp. 7-12, doi: 10.1109/ISCO.2013.6481114.

[3] 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)(48184), Tirunelveli, India, 2020, pp. 111-118, doi: 10.1109/ICOEI48184.2020.9142920.

[4] D. K. Saini, R. Nair, M. Yadav and R. Prasad, "Modified Algorithm for Fault Detection on AC Electrical Traction Line: An Indian Climate Case Study," in IEEE Transactions on Transportation Electrification, vol. 4, no. 4, pp. 936-950, Dec. 2018, doi: 10.1109/TTE.2018.2859379.

[5] L. Wang, Y. Pang, K. -W. Lao, M. -C. Wong, F. Ma and X. Zhou, "Design and Analysis of Adaptive Impedance Structure for Cophase Railway Traction Supply Power Quality Conditioner," in IEEE Transactions on Transportation Electrification, vol. 6, no. 3, pp. 1338-1354, Sept. 2020, doi: 10.1109/TTE.2020.3005665.

[6] S. M. Mousavi Gazafrudi, A. Tabakhpour Langerudy, E. F. Fuchs and K. Al-Haddad, "Power Quality Issues in Railway Electrification: A Comprehensive Perspective," in IEEE Transactions on Industrial Electronics, vol. 62, no. 5, pp. 3081-3090, May 2015, doi: 10.1109/TIE.2014.2386794.

[7] S. Wang et al., "Hybrid phase-controlled circuit breaker with switch system used in the railway auto-passing neutral section with an electric load," in CSEE Journal of Power and Energy Systems, vol. 5, no. 4, pp. 545-552, Dec. 2019, doi: 10.17775/CSEEJPES.2018.00720.

[8] Tsai-Hsiang Chen, "Criteria to estimate the voltage unbalances due to high-speed railway demands," in IEEE Transactions on Power Systems, vol. 9, no. 3, pp. 1672-1678, Aug. 1994, doi: 10.1109/59.336089.

[9] Qing-Chang Zhong; Tomas Hornik, "Power Quality Issues in Traction Power Systems," in Control of Power Inverters in Renewable Energy and Smart Grid Integration , IEEE, 2012, pp.173-184, doi: 10.1002/9781118481806.ch9.

[10] Y. Chen, M. Chen, Z. Tian and Y. Liu, "Voltage Unbalance Management for High-Speed Railway Considering the Impact of Large-Scale DFIG-Based Wind Farm," in IEEE Transactions on Power Delivery, vol. 35, no. 4, pp. 1667-1677, Aug. 2020, doi: 10.1109/TPWRD.2019.2949563.

[11] M. Zare, A. Y. Varjani, S. Mohammad Dehghan and S. Kavehei, "Power Quality Compensation and Power Flow Control in AC Railway Traction Power Systems," 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC), Shiraz, Iran, 2019, pp. 426-432, doi: 10.1109/PEDSTC.2019.8697653.

[12] A. P. Martins, V. A. Morais and C. J. Ramos, "Analysis of the STATCOM/Balancer Robustness in Railway Applications," 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Setubal, Portugal, 2020, pp. 69-75, doi: 10.1109/CPE-POWERENG48600.2020.9161641.

[13] K. Lao, M. Wong, N. Dai, C. Wong and C. Lam, "A Systematic Approach to Hybrid Railway Power Conditioner Design With Harmonic Compensation for High-Speed Railway," in IEEE Transactions on Industrial Electronics, vol. 62, no. 2, pp. 930-942, Feb. 2015, doi: 10.1109/TIE.2014.2341577.

[14] Zhu Guiping, Chen Jianye and Liu Xiaoyu, "Compensation for the negative-sequence currents of electric railway based on SVC," 2008 3rd IEEE Conference on Industrial Electronics and Applications, Singapore, 2008, pp. 1958-1963, doi: 10.1109/ICIEA.2008.4582862.

[15] Z. Shu, S. Xie and Q. Li, "Single-Phase Back-To-Back Converter for Active Power Balancing, Reactive Power Compensation, and Harmonic Filtering in Traction Power System," in IEEE Transactions on Power Electronics, vol. 26, no. 2, pp. 334-343, Feb. 2011, doi: 10.1109/TPEL.2010.2060360.

[16] S. Rahmani, A. Hamadi, K. Al-Haddad and L. A. Dessaint, "A Combination of Shunt Hybrid Power Filter and Thyristor-Controlled Reactor for Power Quality," in IEEE Transactions on Industrial Electronics, vol. 61, no. 5, pp. 2152-2164, May 2014, doi: 10.1109/TIE.2013.2272271.

[17] V. P. Joseph and J. Thomas, "Power quality improvement of AC railway traction using railway static power conditioner a comparative study," 2014 International Conference on Power Signals Control and Computations (EPSCICON), Thrissur, India, 2014, pp. 1-6, doi: 10.1109/EPSCICON.2014.6887509.

[18] M. Habibolahzadeh, H. M. Roudsari, A. Jalilian and S. Jamali, "Improved Railway Static Power Conditioner Using C-type Filter in Scott Co-phase Traction Power Supply System," 2019 10th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC), Shiraz, Iran, 2019, pp. 355-360, doi: 10.1109/PEDSTC.2019.8697499.

[19] X. He et al., "Advanced Cophase Traction Power Supply System Based on Three-Phase to Single-Phase Converter," in IEEE Transactions on Power Electronics, vol. 29, no. 10, pp. 5323-5333, Oct. 2014, doi: 10.1109/TPEL.2013.2292612.

[20] 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), Singapore, 2018, pp. 1-5, doi: 10.1109/ICIRT.2018.8641605.

[21] H. Saad, K. Jacobs, W. Lin and D. Jovcic, "Modelling of MMC including half-bridge and Full-bridge submodules for EMT study," 2016 Power Systems Computation Conference (PSCC), Genoa, Italy, 2016, pp. 1-7, doi: 10.1109/PSCC.2016.7541008.

[22] M. Alharbi, S. Isik and S. Bhattacharya, "Reliability Comparison and Evaluation of MMC Based HVDC Systems," 2018 IEEE Electronic Power Grid (eGrid), Charleston, SC, 2018, pp. 1-5, doi: 10.1109/eGRID.2018.8598662.

[23] D. H. R. Suriyaarachchi, C. Karawita and M. Mohaddes, "Applicability of full-bridge and half-bridge MMC for tapping LCC HVDC," 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Manchester, UK, 2017, pp. 1-6, doi: 10.1049/cp.2017.0049.

[24] F. Qin, F. Gao, Y. Tang, J. Wang and T. Xu, "Comprehensive comparisons between six-arm and nine-arm modular multilevel converter," in CPSS Transactions on Power Electronics and Applications, vol. 5, no. 2, pp. 135-146, June 2020, doi: 10.24295/CPSSTPEA.2020.00012.

[25] F. Zhao, G. Xiao, D. Yang, M. Liu, X. Han and B. Liu, "A novel T-type half-bridge cell for modular multilevel converter with DC fault blocking capability," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-6, doi: 10.1109/ECCE.2016.7854749.