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Shaping the Input Side Current Waveform of a 3-ϕ Rectifier into a Pure Sine Wave

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Abstract**—**In this investigative research paper, we have presented the simulation results of a three-phase rectifier circuit to improve the input side current using the passive filters, such as capacitors and inductors at the output and input terminals of the rectifier circuit respectively. All simulation works were performed in a personal computer using the PSPICE simulator software, which is a virtual circuit design and simulation software package. The output voltages and currents were measured across a resistive load of 1 kΩ. We observed that the output voltage levels, input current wave shapes, harmonic contents through the harmonic spectrum, and total harmonic distortion improved due to the use of such filters.

Keywords**—**Input current wave, three-phase rectifier, passive filter, PSPICE Simulation.

I. Introduction

THE rectification is a process to translate an alternating current (AC) signal into a direct current (DC) signal [1]. This process is done through an electronic circuit that is called a rectifier [2]. This process is very popular in the fields of power electronics and control, because nowadays, many machines, equipment, electronic appliances, household devices, etc. are run by the DC supply [3]. On the other hand, the power supply that we receive from the distribution company is AC due to some historical reasons [4]. Therefore, we have to rely on the AC supply for the proper operation of many modern devices that run on DC [5]. The usage of rectifiers in the industrial arena began in the age of Mercury converters when electromechanical converters were also used [6]. But today, the rectifier circuit uses semiconductor diodes and other solid-state devices and thus has replaced the vacuum tube, mercury arc valves, etc. However, the process of rectification invites several types of problems, viz. input current distortion, output voltage level degradation, rise in harmonic contents, jitter in the wave shape, etc. [7]. Of these problems, the input current distortion issue is the most vital parameter. To resolve this problem, passive filtering is used in many applications.

There are various ways to categorize rectifier circuits [1], [8]. Based on the number of cycles to be rectified, all rectifier circuits are categorized into two groups, viz.

i) half-wave and
ii) full-wave rectifier.

On the other hand, based on the phases of the input signal, all rectifier circuits are categorized into two more groups, viz.

i) single-phase and
ii) three-phase inputs.

Besides, based on the variation capability of the output voltage, the rectifiers can be grouped into additional two, viz.

i) controlled and
ii) uncontrolled rectifier.

However, based on the source or input type, the rectifiers can be categorized into two more groups, viz.

i) voltage-source rectifier and
ii) current-source rectifier.

Rectifiers are extensively used both in linear and nonlinear loads. There are many important electrical and electronic devices or gadgets where this circuit is used, like charger circuit in a mobile phone battery, uninterrupted power supply (UPS), a discharge lamp, television circuit, computer's switched-mode power supply (SMPS), fax machines, power room of the telecommunication systems, industrial controller circuits, ferromagnetic devices, arc furnaces, energy saver circuits, etc.

The term rectification is very common in the industrial and power electronics fields. In this process, there are a few regulatory issues involved, such as input current nature and amount, harmonic contents, total harmonic distortion, output voltage level, efficiency, etc. concerning duty cycle. These factors are critically analyzed while designing a rectifier circuit. Many research and investigative works have been done in this regard due to the ever-rising demand for rectifiers [9]-[14]. Filtering is an important means to reduce the harmonic contents and thus to make the input current pure sinusoidal. There are two types of filters, viz.

i) Active filter and
ii) Passive filter

Passive filters mainly use capacitors and inductors [15]. Many research experiments were done in the past to investigate the performance level of such filters [14], [16], [17]. In this paper, we tried to improve the input side current of a three-phase rectifier circuit by reducing the total harmonic distortion and at the same time by increasing the output voltage level so that the input current of a three-phase rectifier circuit becomes nearly purely sinusoidal. This also increases efficiency. As such, the size, ratings, and cost of the equipment can be minimized. In this work, appropriate voltage signals with switching frequency and solid-state diodes were used to shape

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the input side current. All of the circuit models and parameters were selected in the PSPICE software package to design and simulate the circuit in a personal computer. The simulation results revealed that the rectified signals improved with the use of passive filters.

II. Literature Review

In the primitive eras, the electrical power system was based on DC power. But suddenly, the electric power generation and distribution turned into AC format. However, the present-day electrical and electronic devices and appliances are DC power-based. There are many areas where we need DC power, such as in electronic controls of the DC-linked motor drive, battery chargers, UPS, instant power supply (IPS), car, engine, home appliances, etc. Therefore, we need to use AC to DC converters [1]. On the other hand, regulatory bodies are imposing stringent requirements. As a result, new areas of research are being evolved gradually.

In modern systems, semiconductor switching devices, such as semiconductor p-n junction diodes, thyristors, and bipolar junction transistors are mostly used for AC-DC conversions [1]. These devices are assumed as being either short or open circuits while they are used as switches. The switching capability of such devices depends on their efficiency and speed of operation. Therefore, these devices have made the power electronics field the fastest-growing research area of electrical and electronic engineering. It is also anticipated that the power dissipation in the device would be minimum while providing a suitable DC voltage.

Passive filtering techniques mainly use capacitors or inductors to reduce low-frequency harmonics [15]. This technique is very much are attractive due to its high reliability, low cost, and design simplicity. But their major drawbacks are size and weight. Of course, active filtering techniques use a high switching frequency converter that shapes the input currents almost sinusoidal with small harmonic contents. But this technique is relatively expensive [18].

If any system is to be addressed as an effective one then a few performance parameters should be considered. Especially, for a rectifier circuit a few parameters, such as purity of the sinusoidal input current, optimum harmonic distortion, correct output voltage level, and higher efficiency are considered as major factors to determine the effectiveness of this circuit [19], [20]. In the past, many researchers have done several research works on these issues. We will describe a few of them in the following paragraphs.

Harmonics are always harmful to the devices. Because, when harmonics are present then non-sinusoidal currents are generated and it affects the system performance severely [21].

In one work, the researchers conducted a comparative analysis of using the capacitors at the AC and DC side to make the input current near sinusoidal and demonstrated its technical and economic advantages [22].

In another work, the power factor improvement based on sinusoidal triangular pulse width modulation technique for a 110 V, 1 kW controlled rectifier circuit was studied with satisfactory results through MATLAB simulation [23].

There are many application-based case studies, models, circuit designs, simulations, and experimentations of various rectifiers were found in the literature [24]-[30]. In one study, we observe that a flipping active-diode rectifier was used to harvest energy from the piezoelectric vibration based on the full-bridge, the active diode, the switch-only, and the flipping-capacitor rectifiers. The simulation results revealed the improved factors for these different types of rectifiers at an input signal frequency of 100 Hz [31].

To have a green computing environment, we need ultra-low-voltage digital logic circuits. As such, diode-based or diode-connected-MOSFET-based rectifiers were analyzed for such low-voltage rectifier circuits. MOSFETs were operated in a weak inversion regime [32].

In another study, a rectifier circuit in microwave frequency was designed to get optimum bandwidth and power. The performance of various rectifiers was analyzed and it was found that the Schottky diode rectifier circuit at RF frequency can provide the AC-DC conversion efficiency of up to 55%. It also provided a low cost at zero bias. However, the performance is mainly affected by the nonlinearity of the input impedance of diodes used in the rectifier circuit. As such, a matching circuit configuration is needed [33].

Models of multilevel converter topologies are gaining popularity in the recent past. However, they have complex procedures of discrete calculations, and thus it is very difficult to converge all state variables within a limited and specified period when we go for real-time implementation. To realize a stable system, the model is split into various sub-systems to get fewer orders of state-space matrices. In another paper, the authors, presented a novel method for decoupling transformer and three cascaded three-level neutral points clamped rectifier modules. Thus, the entire rectifier model could be run within the set time-step of 25 μs. The performance of the rectifier circuit during high dynamic grid voltage and load variations was found good [34].

As the circuits' complexities are increasing day by day, it is, therefore, imperative to design and analyze any circuits using any circuit simulator, such as PSPICE, Multisim, etc. before its practical implementation. It also helps to understand the operation of such circuits, especially for undergraduate students. In one research paper, it was found that a simple half-wave rectifier circuit model was designed using PSPICE to improve the laboratory simulation environment [35].

In this context, in our present work, we made input current pure sinusoidal with high efficiency, high output voltage, and optimum harmonic distortion through PSPIC simulation for a three-phase rectifier circuit. We simulated the designed circuit in the PSPICE with or without inserting the passive filter, such as inductor and capacitor both at the input and output. Moreover, we have changed the elements of the circuit of different values to testify to the results. Besides, we have compared the results to select the best one.

III. Three-Phase Rectifier Circuit

Three-phase diode rectifier circuits are widely used in many high-power and low-cost systems at the expense of power quality decrease because of the harmonic distortion in the current wave shape [36], [37]. A simple three-phase rectifier circuit consists of a three-phase source voltage, six diodes, and a load. We studied such circuits with and without the passive capacitive and inductive filters connected at the output and input sides of the rectifier.

The Harmonic Factor (HF) for a particular harmonic is defined as the ratio of the root mean square (RMS) value of that particular harmonic to the RMS value of the fundamental harmonic component. The Total Harmonic Distortion (THD) on the waveform is defined as the square root of the sum of all HFs [38], [39]. The THD is computed by equation (1):

$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} M_i^2}}{M_1} \times 100\% \qquad (1)$$

where M_i is the magnitude of the *i*-th harmonic constituent and M_1 is the magnitude of the fundamental constituent.

We have explained the rectifier circuits studied in this work. Fig. 1 shows a three-phase diode rectifier circuit without using any passive filter in it. Similarly, Figs. 2-4 show the same circuit by using the capacitive filter at its output, input inductance, and a passive capacitor filter at its output terminal simultaneously, and again input inductance with increased value, and a passive capacitor filter at its output terminal.

IV. Results and Discussions

This section explores the impact of passive filters by simulating the three-phase rectifier circuits shown in the previous section for their input voltage, output voltage, input current, and harmonics contents. The simulation results are shown in various figures in the following sub-sections.

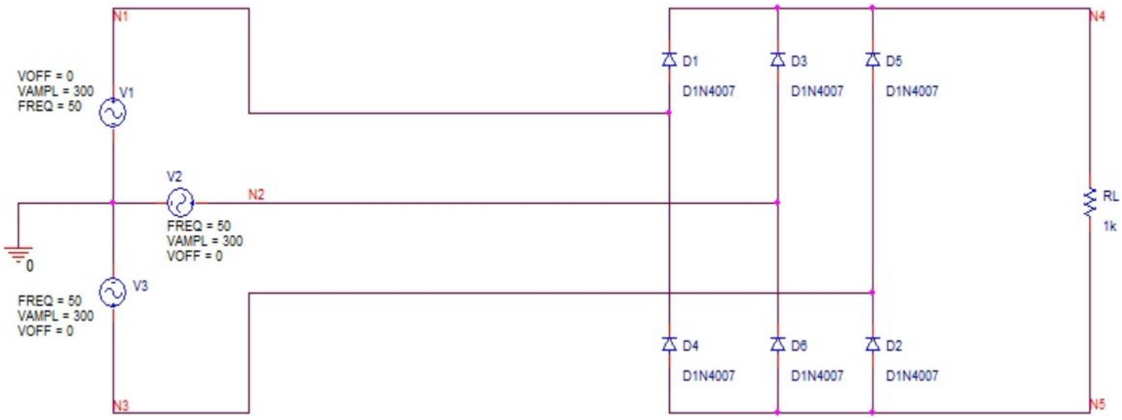

Fig. 1 A simple 3-ϕ diode bridge rectifier circuit without capacitor

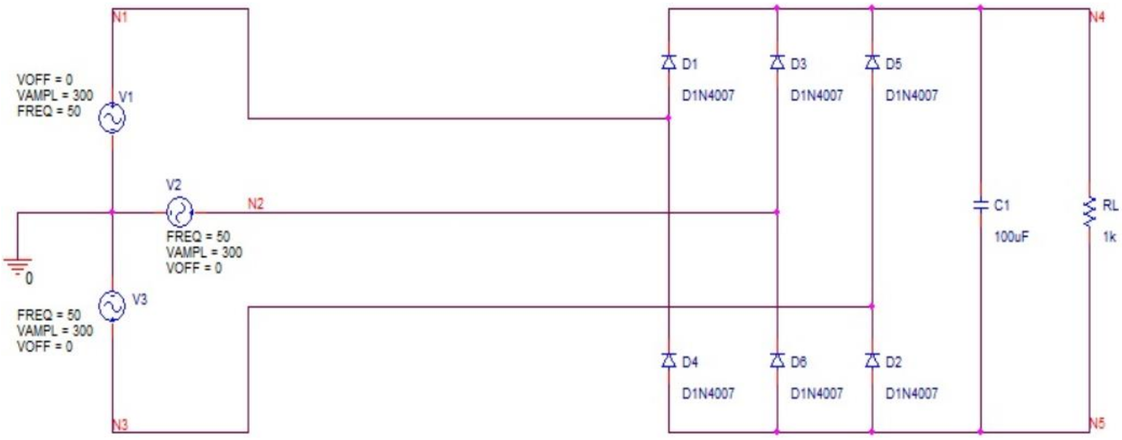

Fig. 2 A simple 3-ϕ diode bridge rectifier circuit with capacitor

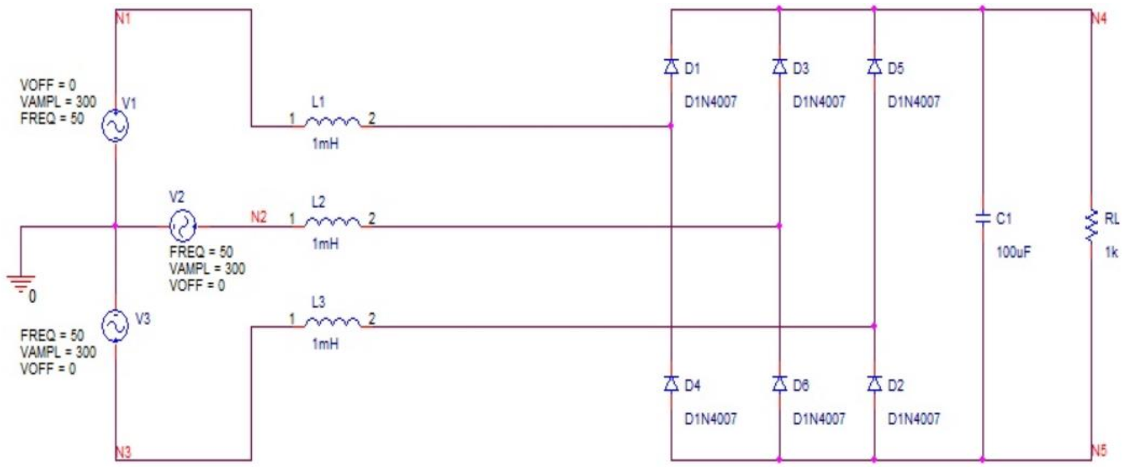

Fig. 3 A simple 3-ϕ diode bridge rectifier with input inductances and a passive capacitor filter at its output terminal

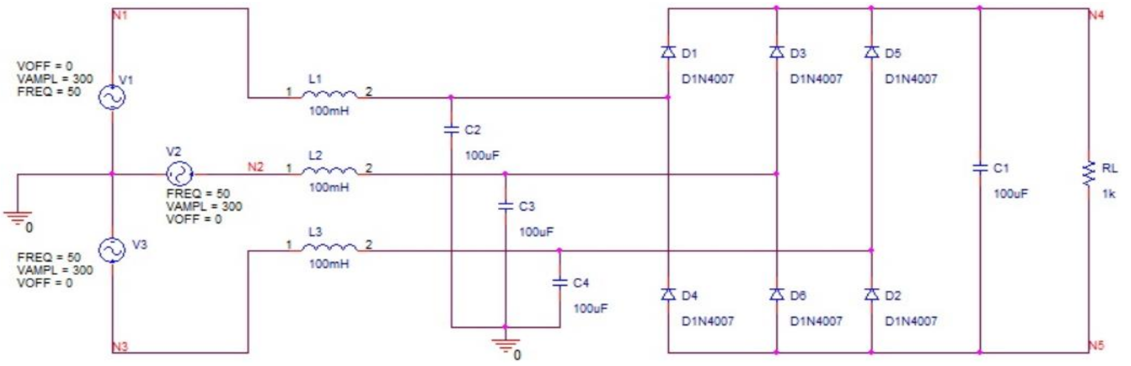

Fig. 4 A simple 3-ϕ diode bridge rectifier with an increased value of the input inductances and a passive capacitor filter at its output terminal

To design and simulate our circuits, the PSPICE software package of version 2015 was used. PSPICE simulation of all the three-phase rectifiers at various operating conditions has been performed in an IBM PC having 500 GB hard disk drive, 4 GB RAM, and an Intel Corei3-2330M processor with 3M L3 cache having a base processing speed of 2.2 GHz clock frequency in Microsoft Windows 10 operating system. In the next sub-sections, the simulation results are demonstrated.

A. Results without Capacitor

Figs. 5-8 show the input voltages, output voltage, input currents, and harmonic contents of the three-phase rectifier circuit. Here, input voltages V_1, V_2, V_3 peak value 300 V with phase difference 120 degrees, frequency 50 Hz, R_1 1000 **Ω**.

The harmonic contents of the input current in phase A without capacitor are presented in Table I.

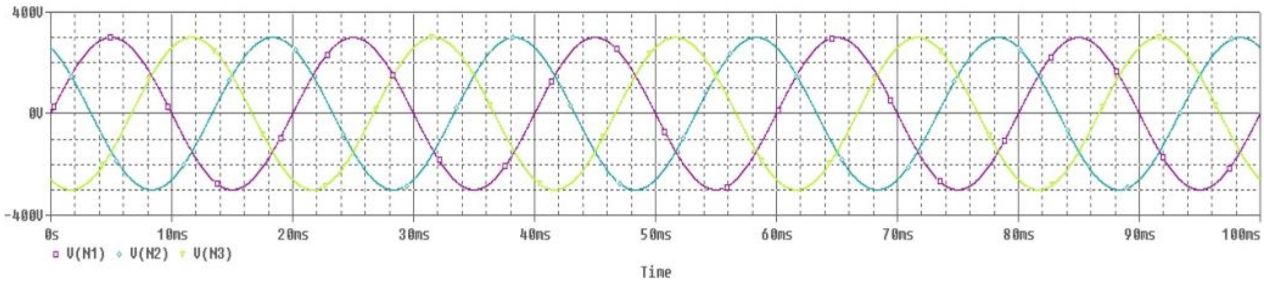

Fig. 5 Input voltages of the rectifier circuit for three phases: A, B, C

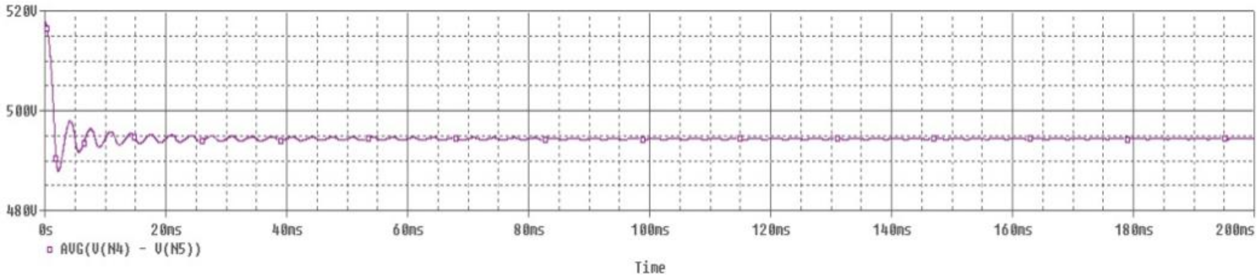

Fig. 6 Output voltage of three-phase rectifier circuit without capacitor

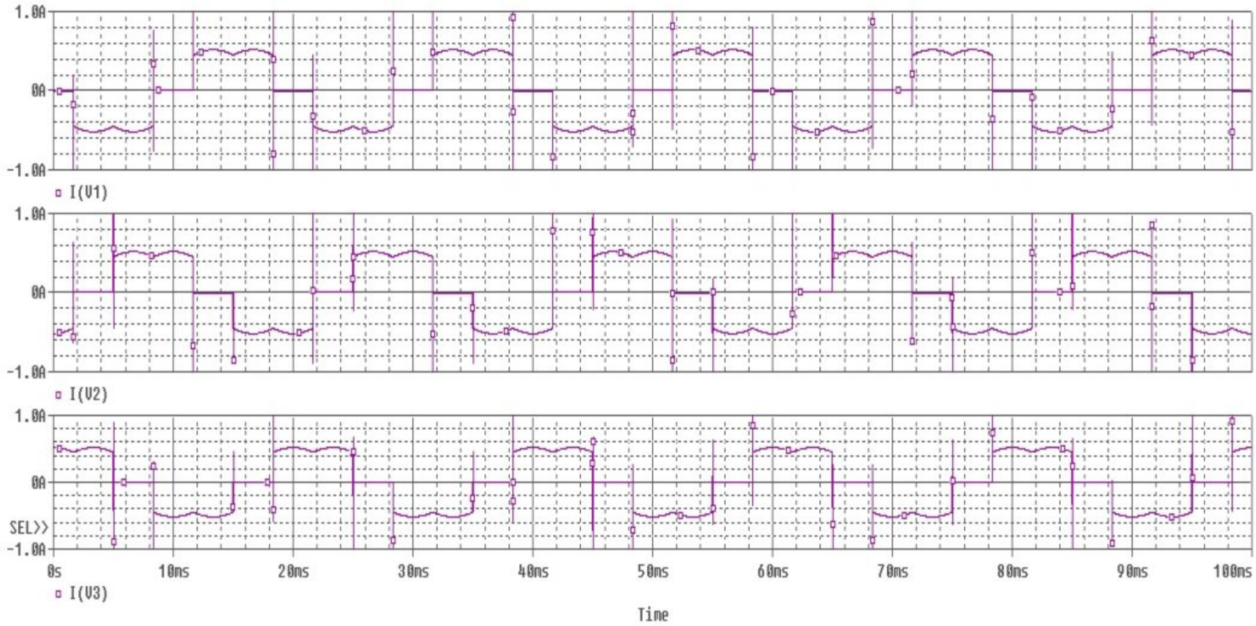

Fig. 7 Input currents of the rectifier circuit for three phases- A, B, C

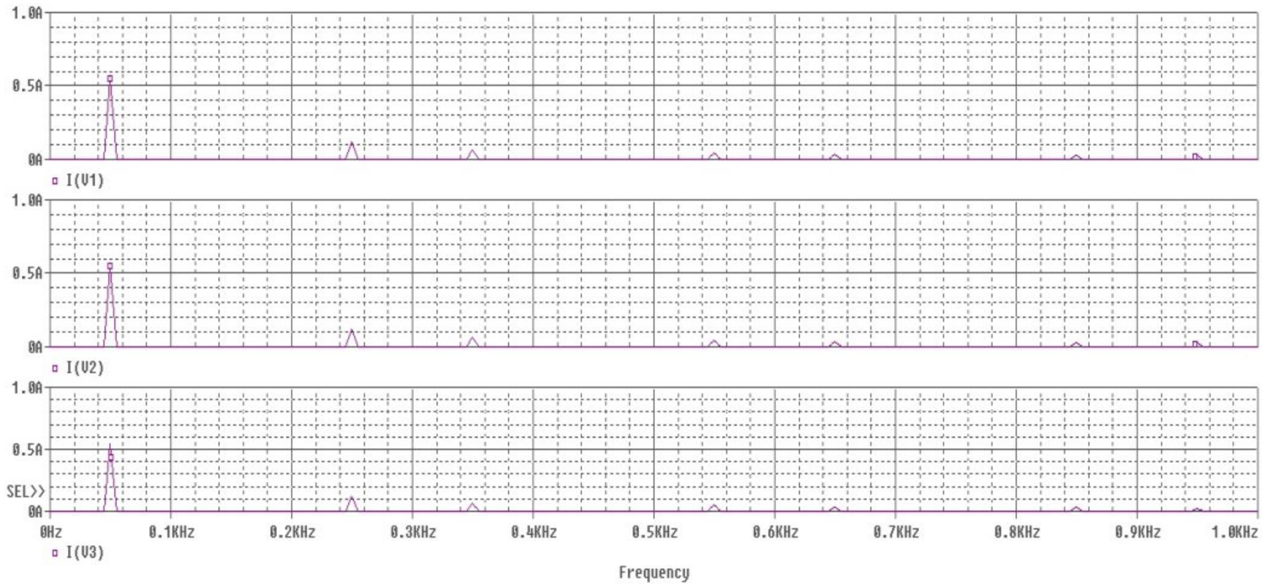

Fig. 8 Harmonic contents of the rectifier circuit for 3 phases-A, B, C

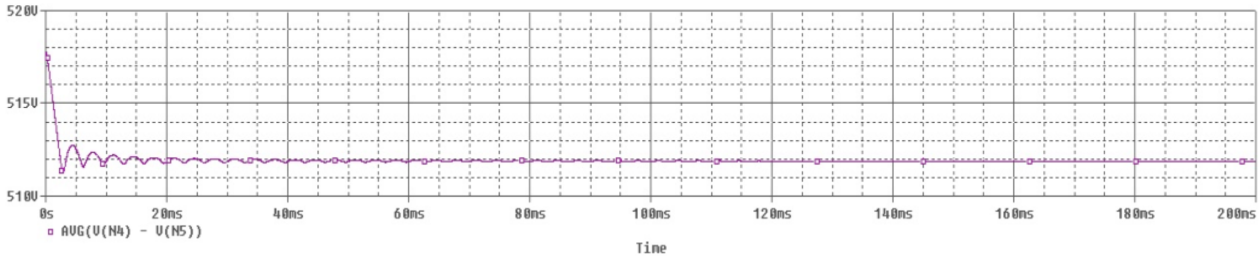

Fig. 9 Output voltage of three-phase rectifier with capacitor

TABLE I
HARMONIC CONTENT OF INPUT CURRENT IN THE PHASE A WITHOUT CAPACITOR

Harmonic Number (Frequency)	Current (mA)
I-1 (50Hz)	546.17
I-2 (100Hz)	0.12
I-3 (150Hz)	0.12
I-4 (200Hz)	0.12
I-5 (250Hz)	123.59
I-6 (300Hz)	0.23
I-7 (350Hz)	68.81
I-8 (400Hz)	0.12
I-9 (450Hz)	0.12
I-10 (500Hz)	0.12
I-11 (550Hz)	49.38
I-12 (600Hz)	0.23
I-13 (650Hz)	35.36
I-14 (700Hz)	0.12
I-15 (750Hz)	0.12
I-16 (800Hz)	0.12
I-17 (850Hz)	30.84
I-18 (900Hz)	0.23
I-19 (950Hz)	24.75
I-20 (1000Hz)	0.12

Putting the values of Table I in (1), we got the THD values for a simple rectifier is 28.64%.

B. Results with Capacitor

Figs. 9-11 show the input voltages, output voltage, input currents, and harmonic contents of the three-phase rectifier circuit. Here, input voltages V_1, V_2, V_3 peak value 300 V with phase difference 120 degrees, frequency 50 Hz, R_1 1000 Ω.

The THD obtained from the rectifier is 185%. This is an extremely large value. Because of the insertion of the capacitor at the output to make the output voltage ripple-free, the input current becomes too distorted, and harmonic content has increased a lot.

C. Harmonic Reduction with Passive Filter at Input Side

By observing the input current wave shape of these filters, we can say about the harmonic contents of them. There are no even harmonics as the waveforms are symmetrical about the *x*-axis. Another noteworthy point is that if the load is balanced then a three-phase rectifier does not produce a third or its multiple harmonic constituents. However, the magnitudes of the 11th and higher-order harmonic components reduce significantly to their lowest level. Thus, only the 5th and 7th order harmonics can cause problems for AC drives.

TABLE II
HARMONIC CONTENT OF INPUT CURRENT IN THE PHASE A WITH CAPACITOR

Harmonic Number (Frequency)	Current (mA)
I-1 (50Hz)	589.837
I-2 (100Hz)	0.002
I-3 (150Hz)	0.192
I-4 (200Hz)	0.002
I-5 (250Hz)	562.848
I-6 (300Hz)	0.002
I-7 (350Hz)	537.044
I-8 (400Hz)	0.002
I-9 (450Hz)	0.002
I-10 (500Hz)	0.002
I-11 (550Hz)	465.233
I-12 (600Hz)	0.002
I-13 (650Hz)	422.392
I-14 (700Hz)	0.002
I-15 (750Hz)	0.002
I-16 (800Hz)	0.002
I-17 (850Hz)	330.294
I-18 (900Hz)	0.002
I-19 (950Hz)	285.302
I-20 (1000Hz)	0.002

Passive filters may be used to reduce the harmonics content of the output currents. However, with these filters, we cannot adjust the output voltage levels but the output voltage levels are diminished in comparison to that of the without filter cases. The simulation results with only various values of inductances of the inductive filters (1 mH, 100 mH, and 1 H) at the input side only are shown in Figs. 12-14. From the wave shapes of these figures, we observed that as the value of the inductor increases, the input wave shapes are improving a lot but the output voltage level decreases. We also observed that the decreasing of the value of inductors gives more output voltage and more input current distortions.

D. Harmonic Reduction with Passive Filters at Both Input and Output Sides

From the wave shapes shown in Figs. 15-20, we see that the values of the inductors and capacitors increase at the input and output terminals respectively, the input current wave shapes improve a lot but at the same time the value of the output voltage level increases without input current wave distortion.

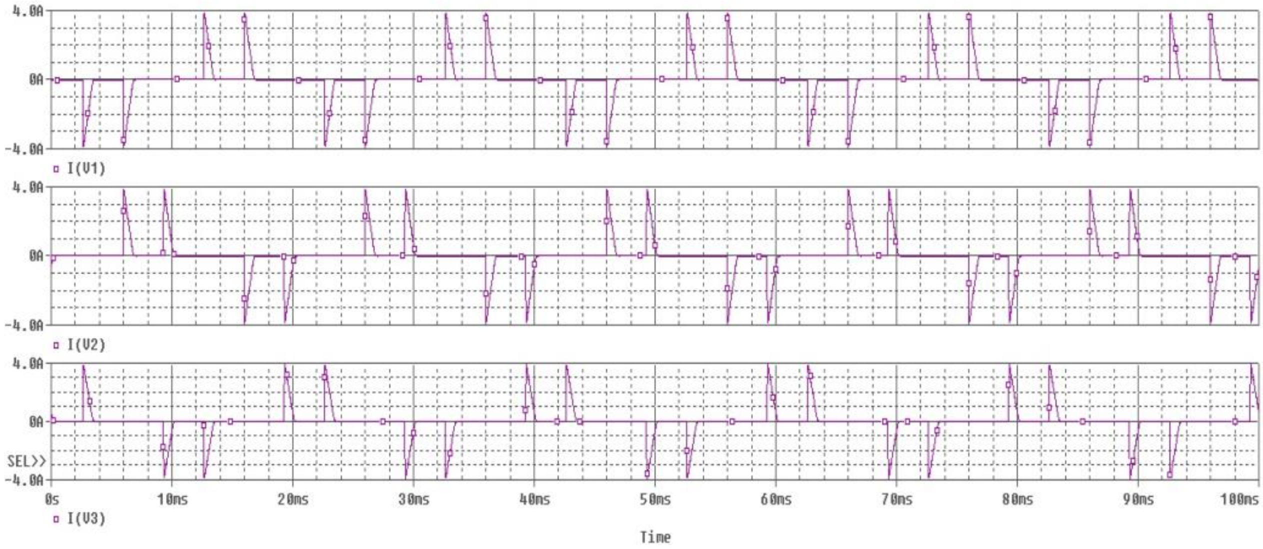

Fig. 10 Input currents of the three phases of the rectifier with capacitor

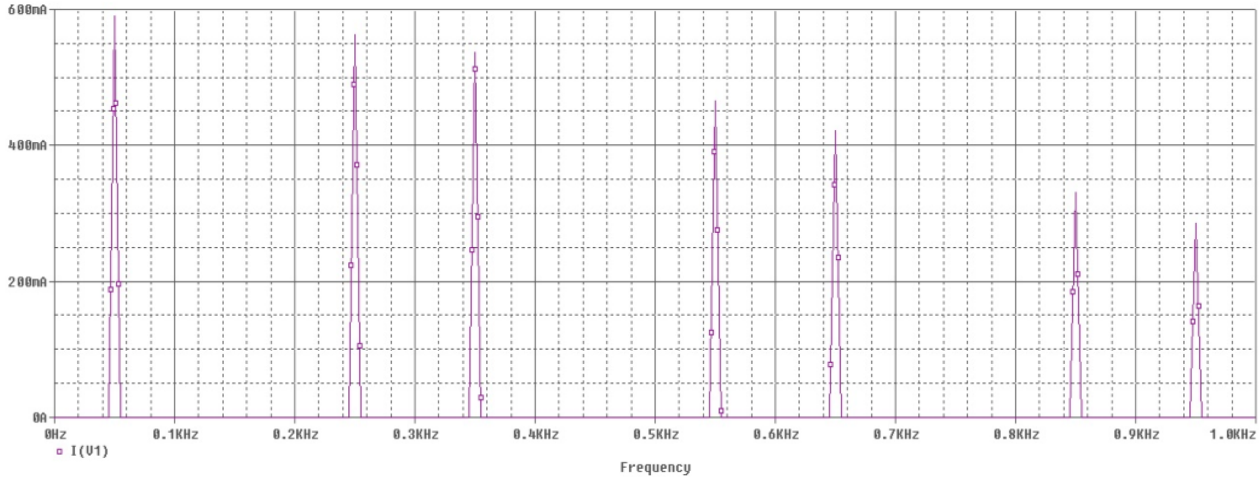

Fig. 11 Harmonic content of phase A for three-phase rectifier with capacitor

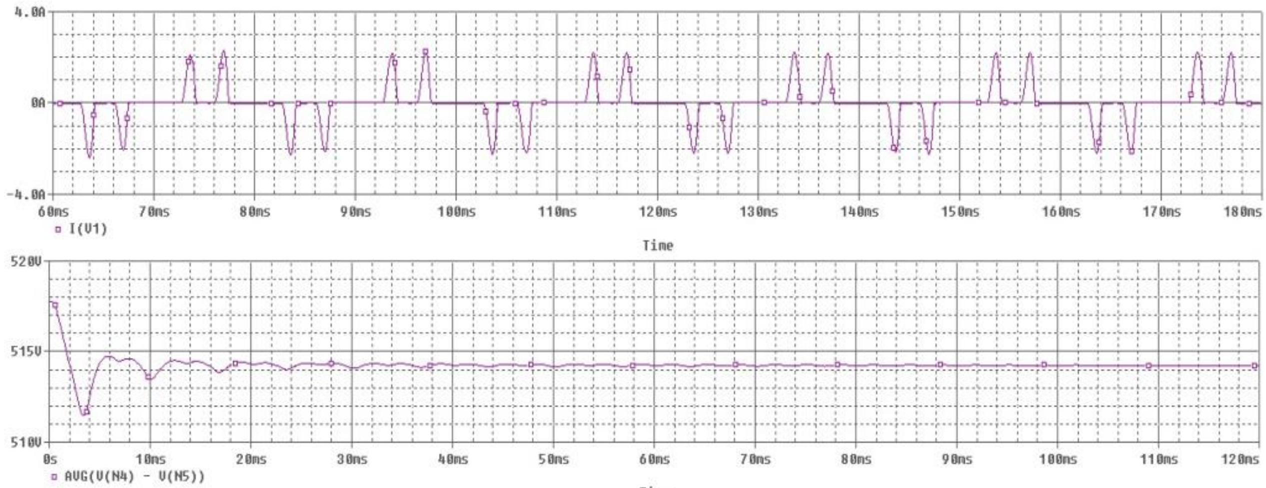

Fig. 12 Input current and output voltage with $L_1 = L_2 = L_3 = 1$ mH

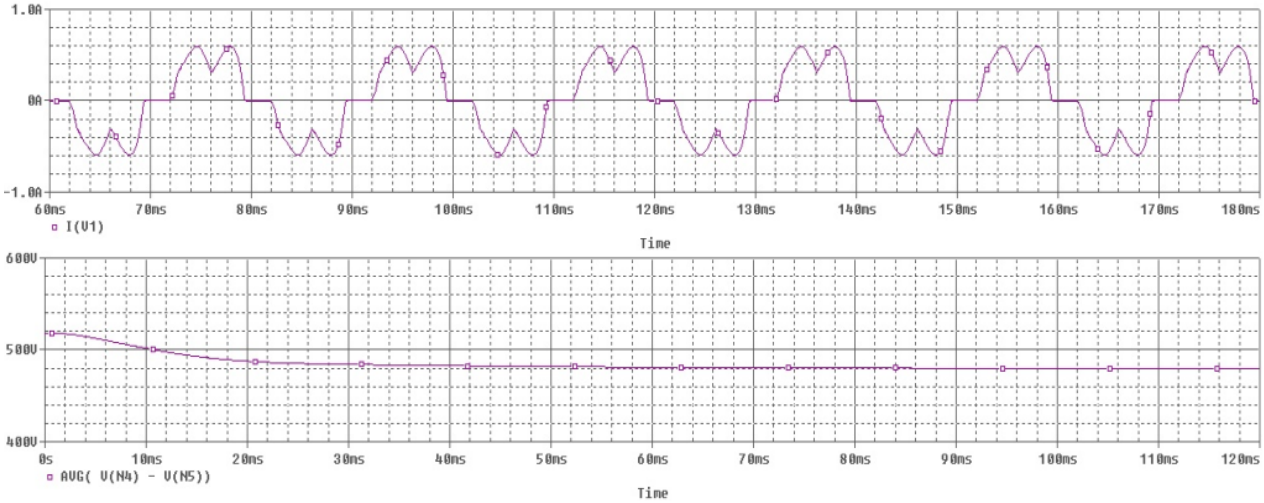

Fig. 13 Input current and output voltage with $L_1 = L_2 = L_3 = 100$ mH

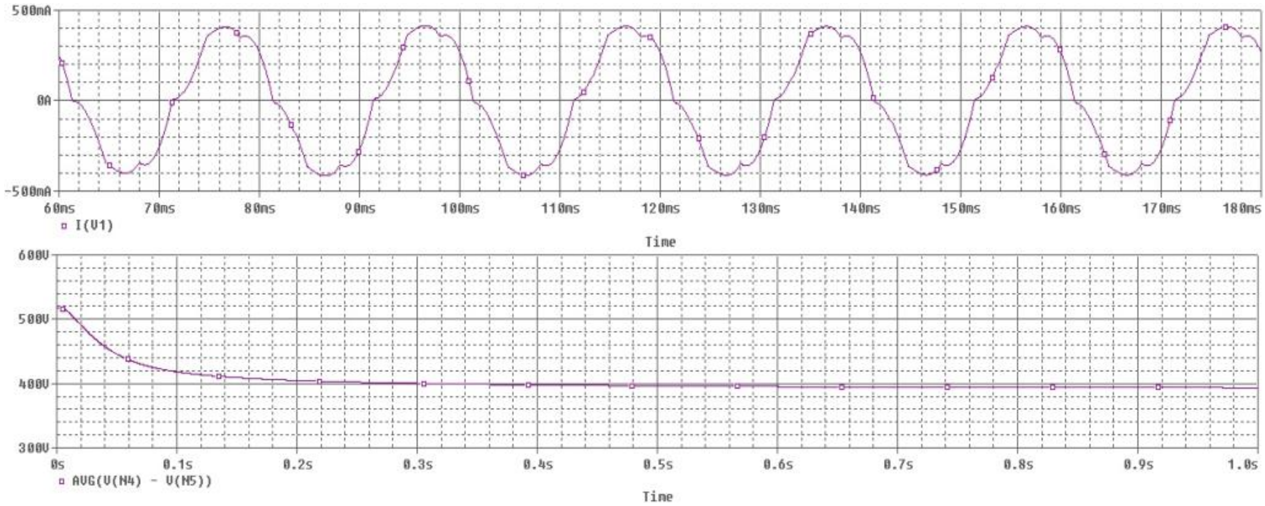

Fig. 14 Input current and output voltage with $L_1 = L_2 = L_3 = 1$ H

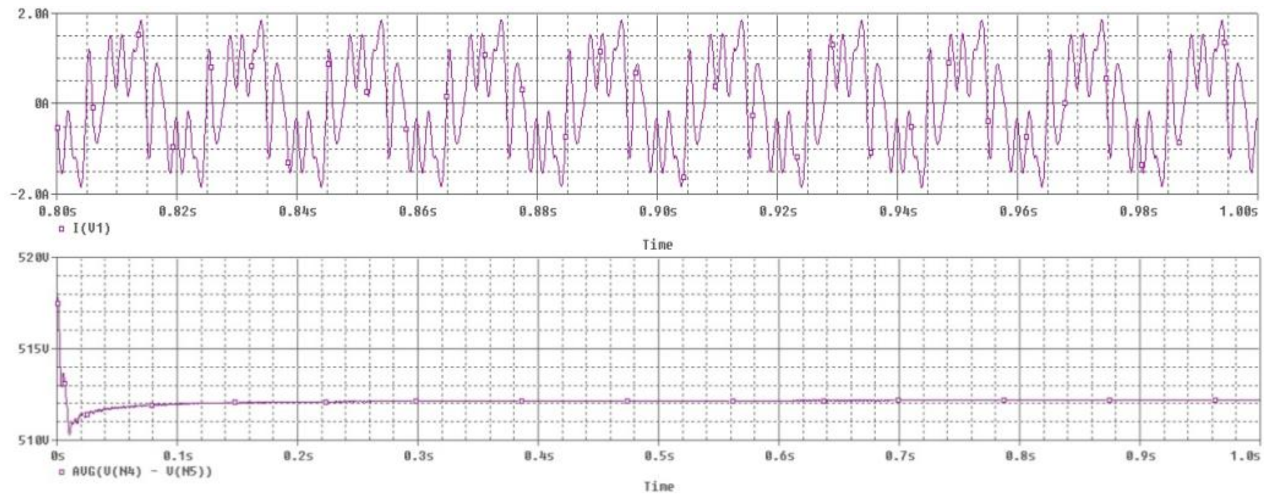

Fig. 15 Input current and output voltage with $L_1 = L_2 = L_3 = 10$ mH and $C_1 = C_2 = C_3 = 10$ μF

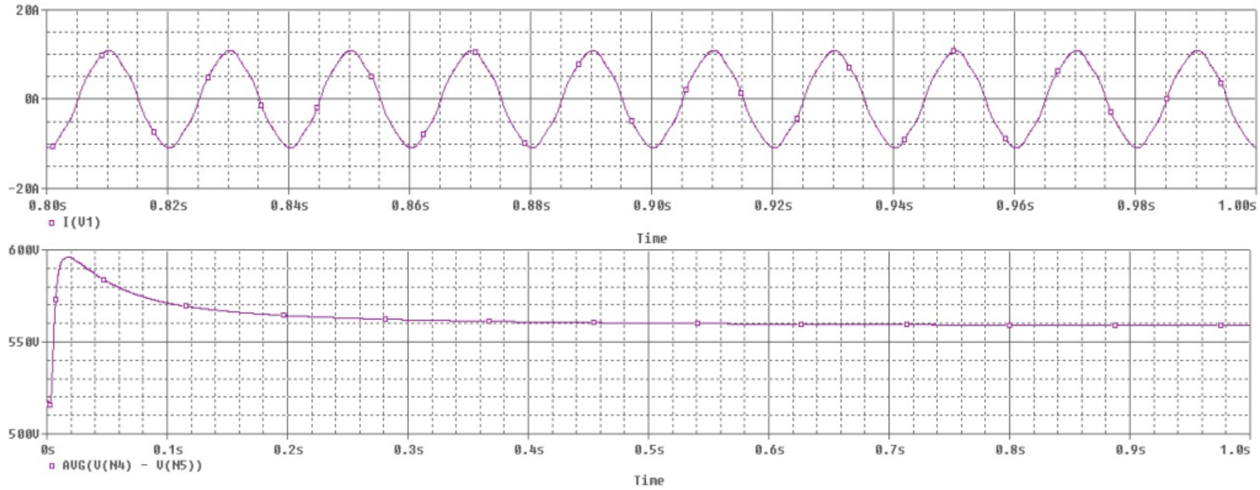

Fig. 16 Input current and output voltage with $L_1 = L_2 = L_3 = 10$ mH and $C_1 = C_2 = C_3 = 100$ µF

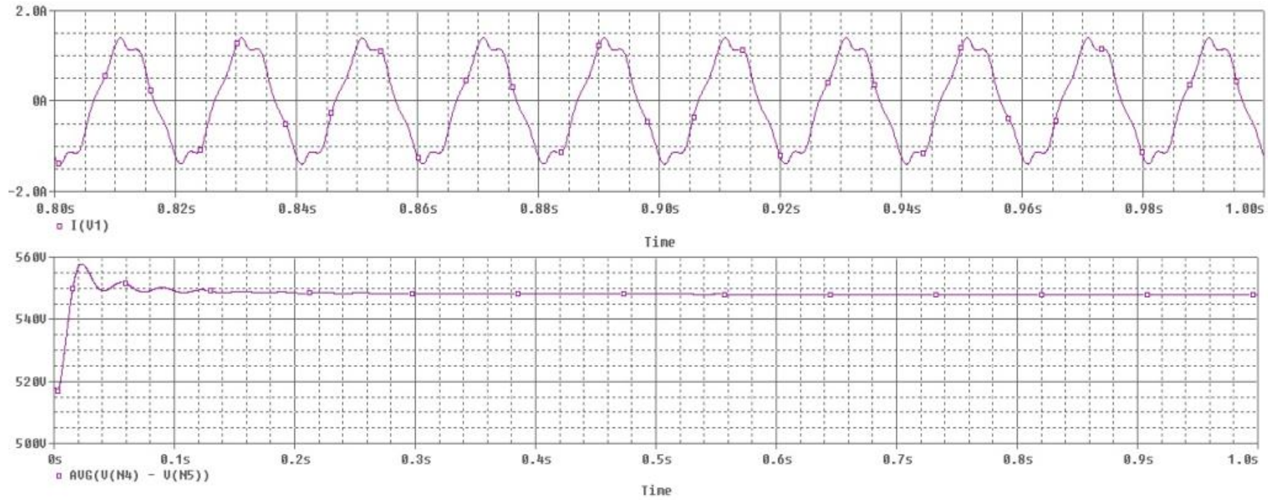

Fig. 17 Input current and output voltage with $L_1 = L_2 = L_3 = 100$ mH and $C_1 = C_2 = C_3 = 10$ µF

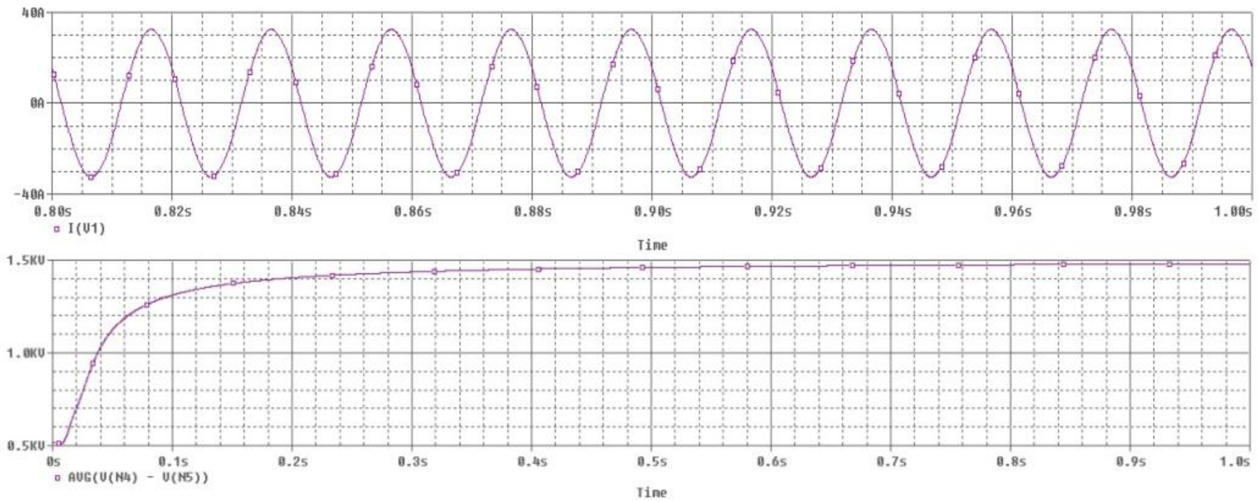

Fig. 18 Input current and output voltage with $L_1 = L_2 = L_3 = 100$ mH and $C_1 = C_2 = C_3 = 100$ µF

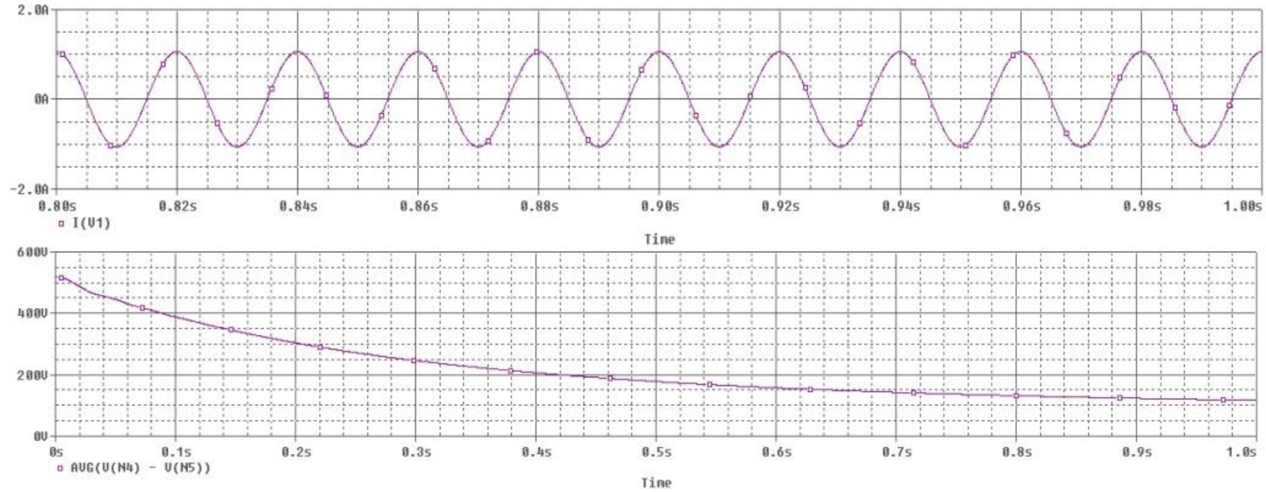

Fig. 19 Input current and output voltage with $L_1 = L_2 = L_3 = 1$ H and $C_1 = C_2 = C_3 = 100$ μF

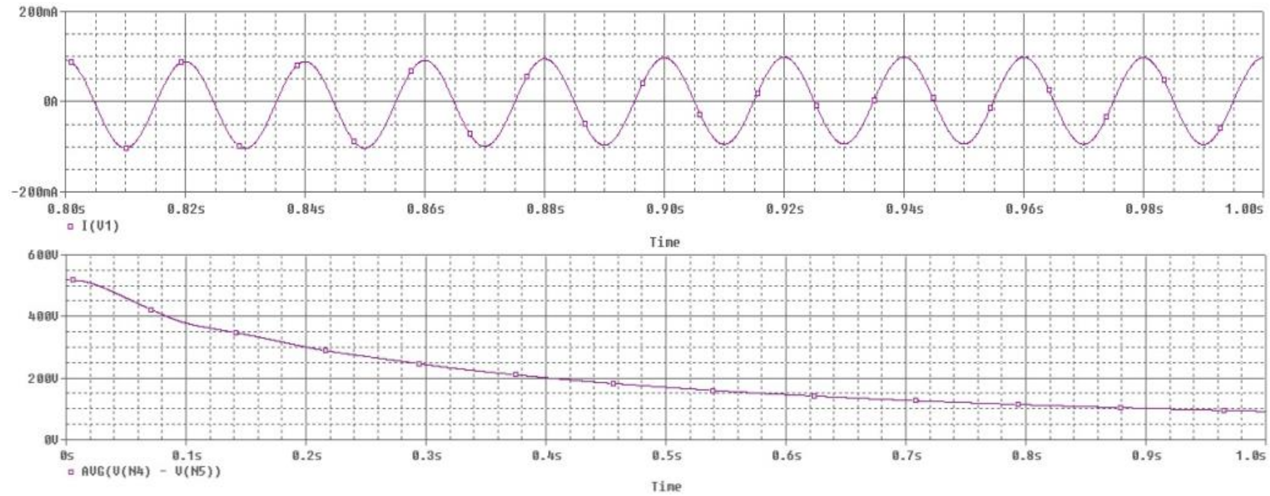

Fig. 20 Input current and output voltage with $L_1 = L_2 = L_3 = 10$ H and $C_1 = C_2 = C_3 = 100$ μF

The best model for the passive filter was obtained when L = 100 mH and C = 100 μF. The filter can be modeled by calculating the resonance frequency values by setting $X_L = X_C$. The calculation is performed by considering the fundamental component as 50 Hz. The product of LC should be 1×10^{-5}. So, in a passive input filter, the component values are very large and regulation of the output voltage is not possible.

V. Conclusion

In this research paper, a three-phase rectifier circuit was studied in the PSPICE environment. Wave shapes for currents and voltages and the harmonic contents are simulated and analyzed for various combinations of the input inductances and output capacitances. Effects of input inductance and harmonic reduction processes are explained with passive capacitive filters. The simulation results in PSPICE reveal that the harmonic contents can be reduced significantly by the use of input inductances and output capacitances in a three-phase rectifier circuit.

References

[1] A. R. Prasad, D. Phoivos, Ziogas, and S, Manias, "An active power factor correction technique for three phase diode rectifiers," IEEE Trans. on Power Electronics, vol. 6, no.1, January 1999, pp. 83-91.

[2] A. I. Maswood, and E. Firmansyah, "Current injection in a controlled rectifier under unbalanced supply and variable line and load inductances," IET Power Electron., 2009, vol. 2, no. 4, pp. 387-397.

[3] M. H. Rashid, "Power Electronics," 3rd ed., Pearson, USA, 2011.

[4] C. L. Sulzberger, "Triumph of AC. 2. The battle of the currents," IEEE Power and Energy Magazine, vol. 99, no. 4, pp. 70-73, July-Aug. 2003.

[5] W. He, F. Xue, F. Zheng, Y. Zhou, K. Liu, and Y. Tian, "Research on AC & DC hybrid power supply system with high-proportion renewable energy of data centre," The Journal of Engineering, e-ISSN 2051-3305, Volume 2019, issue 16, March 2019, pp. 3230-3233, doi: 10.1049/joe.2018.8925.

[6] H. Rissik, "Mercury-Arc Current Converters," Pitman. 1941.

[7] M. R. Ahmed, Ruma and M. J. Alam, "Improvement of input side current of a three-phase rectifier using Cúk converter in Discontinuous Capacitor-Voltage Mode Operation", 2nd IEEE International Conference on Power and Energy, Johor Baharu, Malaysia, 2008, pp. 1152-1155.

[8] D. Lu, X. Wang and F. Blaabjerg, "Investigation on the AC/DC Interactions in Voltage-Source Rectifiers and Current-Source Rectifiers," 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL), Padua, Italy, 2018, pp. 1-6, doi: 10.1109/COMPEL.2018.8460150.

[9] Asiya et al., "Generalized Analysis and Performance Investigation of the Class-E/Fn Rectifiers," in IEEE Access, vol. 8, pp. 124145-124157, 2020, doi: 10.1109/ACCESS.2020.3005701.

[10] M. Jinno, W.-Lune Wu, and J. C. Doong, "Efficiency improvement for forward DC-DC converter employing synchronous rectifier," IEEE 31st Annual Power Electronics Specialists Conference. Conference Proceedings (Cat. No.00CH37018), Galway, Ireland, 2000, pp. 1516-1521 vol.3, doi: 10.1109/PESC.2000.880531.

[11] A. Kaplon, and J. Rolek, "Analysis of multipulse rectifiers with modulation in DC circuit in vector space approach," 13th International Power Electronics and Motion Control Conference, Poznan, Poland, 2008, pp. 377-382, doi: 10.1109/EPEPEMC.2008.4635294.

[12] R. Li, S. Yoshida, Y. Suzuki, H. Okazaki, and K. Nishikawa, "Investigation of Rectifier Operation with Harmonic Controlled Input Signals towards Pulse Modulation WiCoPT System," IEEE International Symposium on Radio-Frequency Integration Technology, Hiroshima, Japan, 2020, pp. 187-189, doi: 10.1109/RFIT49453.2020.9226251.

[13] P. P. Nachankar, H. M. Suryawanshi, P. Chaturvedi, D. D. Atkar and P. Vijay Vardhan Reddy, "Investigation of Passive Rectifier Circuits for ModularSolid State Transformer Applications," IEEE First International Conference on Smart Technologies for Power, Energy and Control, Nagpur, India, 2020, pp. 1-6, doi: 10.1109/STPEC49749.2020.9297717.

[14] C. Marouchos, M. Darwish, P. Panagiotis Dimitriadis, and A. Neroupou, "Investigation on line current compensation techniques for rectifier circuits," 50th International Universities Power Engineering Conference, Stoke on Trent, UK, 2015, pp. 1-5, doi: 10.1109/UPEC.2015.7339828.

[15] J. C. Das, "Passive filters– potentialities and limitations," IEEE Transactions on Industrial Applications, vol. 40, no. 1, January 2004, pp. 232-241.

[16] S. Jamali, M. A. S. Masoum and S. A. Mousavi, "Influence of controller high pass filter on the performance of shunt hybrid power filter," Australasian Universities Power Engineering Conference, Sydney, NSW, Australia, 2008, pp. 1-6.

[17] G. Xiao, Y. Pei, K. Li, X. Yang, and Z. Wang, "A novel control approach to the DC active power filter used in a low ripple and large stable/pulse power supply," IEEE 34th Annual Conference on Power Electronics Specialist (PESC), Acapulco, Mexico, 2003, vol. 4, pp. 1489-1493, doi: 10.1109/PESC.2003.1217674.

[18] J. C. Das, "Passive filters-potentialities and limitations," Conference Record of the Annual Pulp and Paper Industry Technical Conference, 2003, Charleston, SC, USA, 2003, pp. 187-197, doi: 10.1109/PAPCON.2003.1216916.

[19] J. C. Read, "The Calculations of Rectifier and Inverter Performance Characteristics," JIEE, UK, 1943, pp. 495-509.

[20] D. A. Gonzalez and J. C. McCall, "Design of Filters to Reduce Harmonic Distortion in Industrial Power Systems," IEEE Transactions on Industry Applications, vol. IA-23, no. 3, pp. 504-511, May 1987, doi: 10.1109/TIA.1987.4504938.

[21] S. George, V. Agarwal, "Effect of Harmonics on Reliability of Electrical Equipment," International Conference on Quality, Reliability and Control, ICRC 2001, p. R687.

[22] D. Alexa, A. Sarbu, I. V. Pletea, C. Filote, and R. Chiper, "Variants of rectifiers with near sinusoidal input currents– a comparative analysis with the conventional diode rectifier," IET Power Electronics, vol. 4, issue 6, pp. 632-641, 2011, The Institution of Engineering and Technology, doi: 10.1049/iet-pel.2010.0020.

[23] D. Sajeesh and S. George, "Power factor improvement in rectifier circuit — A simulation study," Annual International Conference on Emerging Research Areas: Magnetics, Machines and Drives (AICERA/iCMMD), Kottayam, India, 2014, pp. 1-5, doi: 10.1109/AICERA.2014.6908237.

[24] R. Lai, F. Wang, R. Burgos, D. Boroyevich, D. Jiang and D. Zhang, "Average Modeling and Control Design for VIENNA-Type Rectifiers Considering the DC-Link Voltage Balance," IEEE Transactions on Power Electronics, vol. 24, no. 11, pp. 2509-2522, Nov. 2009, doi: 10.1109/TPEL.2009.2032262.

[25] J. W. Kolar and F. C. Zach, "A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules," Proceedings of Intelec 94, 1994, pp. 367-374, doi: 10.1109/INTLEC.1994.396642.

[26] J. W. Kolar and U. Drofenik, "A new switching loss reduced discontinuous PWM scheme for a unidirectional three-phase/switch/ level boost-type PWM (VIENNA) rectifier," 21st International Telecommunications Energy Conference. INTELEC1999 (Cat. No.99CH37007), 1999, pp. 572-, doi: 10.1109/INTLEC.1999.794128.

[27] P. Ide, F. Schafmeister, N. Frohleke and H. Grotstollen, "Enhanced control scheme for three-phase three-level rectifiers at partial load," IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 719-726, June 2005, doi: 10.1109/TIE.2005.843959.

[28] G. Gong, M. L. Heldwein, U. Drofenik, J. Minibock, K. Mino and J. W. Kolar, "Comparative evaluation of three-phase high-power-factor AC-DC converter concepts for application in future More Electric Aircraft," IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 727-737, June 2005, doi: 10.1109/TIE.2005.843957.

[29] U. Drofenik, G. Laimer and J. W. Kolar, "Pump Characteristic based optimization of a direct water cooling system for a 10-kW/500-kHz Vienna rectifier," IEEE Transactions on Power Electronics, vol. 20, no. 3, pp. 704-714, May 2005, doi: 10.1109/TPEL.2005.846529.

[30] M. Malinowski, M. P. Kazmierkowski, S. Hansen, F. Blaabjerg and G. D. Marques, "Virtual-flux-based direct power control of three-phase PWM rectifiers," IEEE Transactions on Industry Applications, vol. 37, no. 4, pp. 1019-1027, July-Aug. 2001, doi: 10.1109/28.936392.

[31] W.-L. Wu, C.-Y. Yang and D.-A. Wang, "A Flipping Active-Diode Rectifier for Piezoelectric-Vibration Energy-Harvesting," European Conference on Circuit Theory and Design (ECCTD), Sofia, Bulgaria, 2020, pp. 1-4, doi: 10.1109/ECCTD49232.2020.9218313.

[32] C. Galup-Montoro, M. C. Schneider and M. B. Machado, "Ultra-Low-Voltage Operation of CMOS Analog Circuits: Amplifiers, Oscillators, and Rectifiers," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 59, no. 12, pp. 932-936, December 2012, doi: 10.1109/TCSII.2012.2231042.

[33] Y. Zhou, B. Froppier, and T. Razban, "Study of a matching circuit effect on a microwave rectifier," 11th Mediterranean Microwave Symposium (MMS), Yasmine Hammamet, Tunisia, 2011, pp. 29-33, doi: 10.1109/MMS.2011.6068522.

[34] J. V. Bapiraju, M. Giroux and J. Produkku, "Novel approach for modelling 3-level active rectifiers in real-time simulations," IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, India, 2016, pp. 1-5, doi: 10.1109/PEDES.2016.7914526.

[35] S. Porwal, P. Chhawchharia, and R. Pandey, "Simplified half wave rectifier model for improved laboratory simulation using PSpice," International Conference on Power Electronics and Drive Systems (PEDS), Taipei, Taiwan, 2009, pp. 973-978, doi: 10.1109/PEDS.2009.5385656.

[36] M. Tou, K. Al-Haddad, G. Olivier and V. Rajagopalan, "Analysis and design of single controlled switch three phase rectifier with unity power factor and sinusoidal input current," Proceedings of the IEEE Applied Power Electronics Conference and Exposition - APEC'95, Dallas, TX, USA, 1995, pp. 856-862 vol.2, doi: 10.1109/APEC.1995.469041.

[37] D. Li, Y. Notohara, M. Sano and T. Ando, "Low-cost high-power-factor three-phase rectifier with turn-on current suppression circuit," IEEE Energy Conversion Congress and Exposition, Denver, CO, USA, 2013, pp. 4872-4877, doi: 10.1109/ECCE.2013.6647356.

[38] F. M. Fernandez and P. S. C. Nair, "Influence of power factor compensating capacitors on estimation of harmonic distortion," 9th IEEE International Conference on Electrical Power Quality and Utilisation, Barcelona, Spain, 2007, pp. 1-4, doi: 10.1109/EPQU.2007.4424128.

[39] M. H. Bhuyan, "Digital Signal Processor Controlled PWM Phase Modulator for Two Phase Voltage Source Inverter," MSc Engg. Thesis, Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, 2002.

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