*Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.*
Vol. **62**, *4*, pp. 411–416, Bucarest, 2017

# ASYMMETRICAL CASCADED TWENTY SEVEN LEVEL INVERTER BASED STATCOM

MAHALINGAM RAMYA[1], P. USHA RANI[2]

**Key words: Cascaded H-bridge (CHB), Total harmonic distortion (THD), Artificial neural network controller (ANNC).**

**This paper presents a twenty seven level Asymmetrical cascaded multilevel inverter based STATCOM. The STATCOM is characterized by series connection of low voltage converter, middle level voltage converter and high voltage converter. Asymmetrical switching configuration can be adopted with trinary dc sources. This configuration results in reduced number of switches for higher voltage levels. Artificial neural network controller is used for obtaining switching angles. The performance of twenty seven level inverter based STATCOM is analyzed by MATLAB simulation. The results confirm that harmonic performance is improved and unbalanced load compensation can be achieved effectively.**

## 1. INTRODUCTION

Static synchronous compensator is a shunt device that has been connected in parallel with the transmission line through the interfacing reactor. The reactive power compensation plays a major role in transmission and distribution applications. The STATCOM is a flexible ac transmission device used for voltage regulation, power factor control, and stabilization of power flow [1]. Recently multilevel inverters have been used in many STATCOM applications [2] because of its increased benefits. Among the basic three types of multilevel inverters, cascaded H-bridge (CHB) inverter has the advantage of reduction in number of switching devices. Further symmetrical and asymmetrical switching techniques can be used based on the applications.

Nowadays trinary based hybrid multilevel inverters have been used and attracted more interest because of generating higher voltage levels than symmetrical switching and binary asymmetrical switching [3, 4].The basic hybrid topology in which different pulsed width modulation (PWM) for different bridges or different dc voltages for bridges can be used for STATCOM applications to improve the waveform quality [5]. These converters can produce high voltage levels and voltage balancing can be done easily by properly selecting the switches [6]. The cascaded H-bridge converter with equal DC voltages has been used for STATCOM applications because of high quality output spectrum [5–12].The multilevel topology based on switched capacitor and diode clamped converters can be used for STATCOM applications [13]. In [14], a diode clamped H-bridge with multi output boost rectifier acts as high voltage inverter. This system is very expensive [15, 16].

In literature [17] series connection of three phase full bridge converter and single phase H-bridge converter can be used. The control method used for STATCOM may be based on proportional integral (PI) controller or fuzzy logic controller. Apart from these techniques artificial neural network (ANN) becomes more popular which can be successfully implemented for power electronic applications [18].In this paper STATCOM is characterized by multilevel inverter. Cascaded H-bridge inverter is used with trinary dc sources. A twenty seven level output is derived with three H-bridges. The dc voltage ratio of the inverter is 1:3. Artificial neural network controller based selective harmonic elimination technique is used to obtain the switching angles for the inverter. The switching angles are taken as output by giving modulation index as input to the ANN controller. The network is trained online by using back propagation algorithm (BPA). The ANN controller provides reduced total harmonic distortion (THD) than PI controller. The performance of the STATCOM has been tested by MATLAB simulation. The results confirm that the use of ANN controller will reduce the harmonics present in the inverter output voltage.

## 2. ASYMMETRICAL CASCADED TWENTY SEVEN LEVEL INVERTER

A multilevel converter has several advantages over conventional converters which can be briefly summarized as follows: improved waveform quality, low total harmonic distortion, high power handling capacity, reduction in switching losses, thereby increasing the overall performance of the system. The various types of multilevel inverters are switched capacitor multilevel inverter, diode clamped multilevel inverter, and cascaded H-bridge multilevel inverter (MLI). Among these three types cascaded H-bridge MLI can be used in many applications because they need reduced number of switches for producing higher voltage levels.

Asymmetrical switching configuration can be effectively used in CHB inverter in which different H-bridges are controlled by different dc voltages. These different dc voltages may be in binary or trinary proportions. The trinary based asymmetrical switching successfully produces more number of voltage levels than binary and symmetrical switching techniques. The number of levels in symmetrical switching will be $[2n+1]$ and for binary asymmetrical configuration it is $[2^{n+1}–1]$. The trinary based asymmetrical configuration the number of output level will be $3^n$ where n represents number of H-bridges.

A twenty seven level inverter is designed by using three H-bridges. ACMLI based twenty seven level inverter with ANN controller in Fig 1 consists of three H-bridges. Upper Bridge is characterized as low level converter with a voltage of 20 V and center bridge represents middle level converter with a dc voltage of 60 V. The lower bridge represents high level converter with a dc voltage of 180 V. The switching pattern follows multiples of three 1:3.

---

[1] E.G.S Pillay Engineering College, Department of EEE, Nagapattinam, India, Email: ramyaegsp.eee@gmail.com

[2] R.M.D Engineering College, Department of EEE, Kavarapettai, Chennai, India, Email: pur.eee@rmd.ac.in

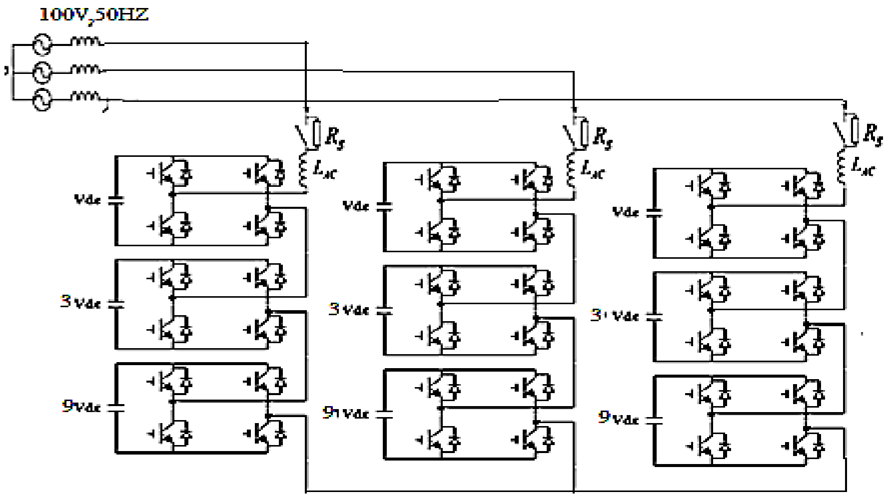


Fig. 1 – Circuit diagram of ACMLI based STATCOM using trinary dc sources.

## 3. ARTIFICIAL NEURAL NETWORK

Number of artificial neurons can be interconnected to form a neural network that simulates the central brain system. The appropriate switching angles of PWM inverter for a given modulation index can be generated by using NN. While using ANN controller it is necessary to train the NN either online or offline. During online training the weights and biases can be changed which is more suitable for nonlinear conditions [18]. But in offline training the weights and biases are fixed. There are two types of control algorithms can be used. They are forward propagation algorithm and backward propagation algorithm [19].

A typical multilayer ANN consists of an input layer, a middle layer, and an output layer. Here ANN has single input layer, one hidden layer and n output layer. The output of the neuron is represented by,

$$\chi = \beta \ (W_0 \textstyle\sum_{i=1}^{k} (W_i + Y_i)). \tag{1}$$

Each of the input signal flows through gain or weight. All these input weighted signals are accumulated by the summing node and then passes to the output through transfer function. The transfer function normally used will be sigmoid, inverse-tan, hyperbolic, or Gaussian type.

The expression for transfer function (sigmoid) used here is given by

$$\beta_1(y) = \frac{1}{\left(1 + e^{-\mu x}\right)}. \tag{2}$$

The Gaussian transfer function is expressed as

$$\beta_2(y) = e^{-\left(\frac{(\mu-\omega)}{\beta_1}\right)^2}. \tag{3}$$

Back propagation algorithm is most commonly used in many applications. The Fig. 2 shows training of ANN for selective harmonic elimination. Modulation index is given as input and switching angle is taken as output. The output is represented by

$$\theta_i = \beta_1\left(\sum_{j=1}^{i} V_{ij}\beta_2\left(m, w_j\right)\right). \tag{4}$$

The steps in training algorithm can be summarized as follows:

- Assign arbitrary weights to the hidden layer and output layer. Input layer is assigned with unity weight.
- Modulation index is given as input and back propagation error has been determined by
  $$E = V_t - V_o.$$
- The weights can be changed based on the propagation error. the change in weight is given by
  $$\Delta w = \delta V_o E$$
  and $\delta$, $E$ represents learning rate and error.
- The new weights are determined as $w = w + \Delta w$.
- The training process has been repeated until the error has reduced to least value.

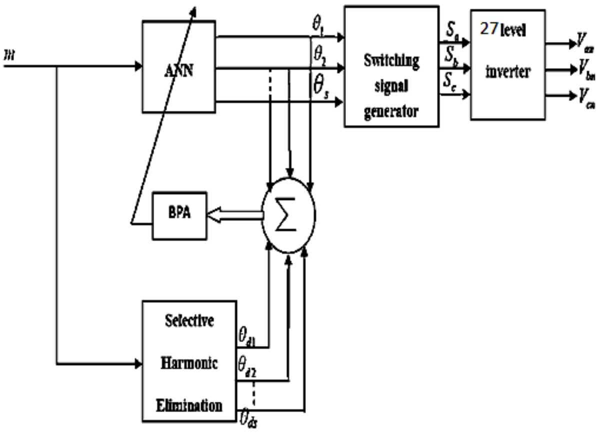


Fig. 2 –Block diagram of ANN based selective harmonic elimination technique.

The block diagram of ANN controller for selective harmonic elimination technique has been used for producing switching angles in Fig 2. The neural network has been trained to eliminate third and fifth harmonic in the inverter output. The lower order harmonics in the inverter output will be effectively reduced without any filter circuit by using this control method. The single input multiple outputs ANN for selective harmonic elimination is used in which the input layer is fed by modulation index whereas switching angles are extracted from the output layer.

*Table 1*

Switching angle generated through ANN controller

| M | $\theta_1$(rad) | $\theta_2$(rad) | $\theta_3$(rad) | $\theta_4$(rad) | $\theta_5$(rad) | $\theta_6$(rad) | $\theta_7$(rad) | $\theta_8$(rad) | $\theta_9$(rad) | $\theta_{10}$(rad) | $\theta_{11}$(rad) | $\theta_{12}$(rad) | $\theta_{13}$(rad) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.4 | 0.236 | 0.134 | 0.112 | 0.412 | 0.522 | 0.731 | 0.433 | 0.613 | 0.333 | 0.214 | 0.423 | 0.532 | 0.267 |
| 0.5 | 0.112 | 0.145 | 0.312 | 0.221 | 0.512 | 0.311 | 0.621 | 0.432 | 0.223 | 0.213 | 0.221 | 0.311 | 0.110 |
| 0.6 | 0.321 | 0.322 | 0.412 | 0.117 | 0.413 | 0.622 | 0.433 | 0.312 | 0.155 | 0.611 | 0.222 | 0.301 | 0.218 |
| 0.7 | 0.119 | 0.154 | 0.257 | 0.611 | 0.321 | 0.478 | 0.611 | 0.111 | 0.172 | 0.332 | 0.101 | 0.238 | 0.412 |
| 0.8 | 0.221 | 0.412 | 0.523 | 0.223 | 0.134 | 0.513 | 0.463 | 0.552 | 0.199 | 0.213 | 0.412 | 0.456 | 0.319 |
| 0.9 | 0.112 | 0.199 | 0.254 | 0.318 | 0.423 | 0.221 | 0.387 | 0.421 | 0.344 | 0.511 | 0.119 | 0.223 | 0.155 |
| 1.0 | 0.155 | 0.177 | .288 | 0.623 | 0.713 | 0.662 | 0.425 | 0.213 | 0.412 | 0.188 | 0.320 | 0.623 | 0.417 |

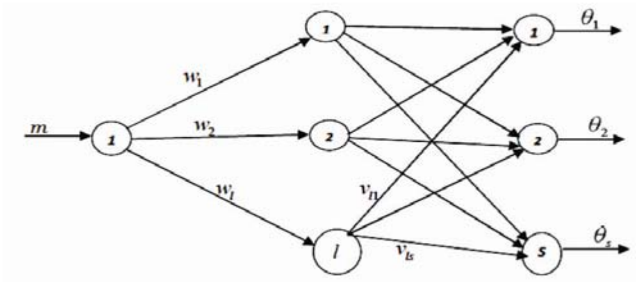


Fig. 3 – ANN set for selective harmonic elimination technique.

Figure 3 shows the multiple output layers ANN set for inverter control. The input data given to input layer has been distributed to all the neurons in middle layer by input layer. The middle layer act as a detector which encodes the weight. The output layer receives the data from middle layer and passes a result to transfer function. The number of hidden layers and neurons in the hidden layer purely depends on the design aspects and there is no common rule for the selection of number of hidden layers and neurons.

## 4. SELECTIVE HARMONIC ELIMINATION (SHE) STRATEGY

Let us consider a single H-bridge which consists of four switches as shown in Fig. 4.

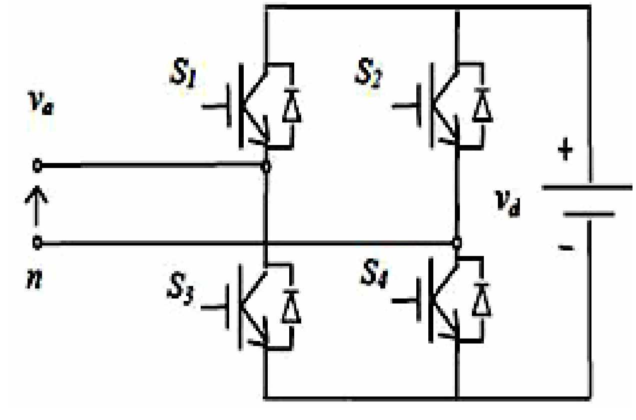


Fig. 4 – Structure of single H-bridge.

During positive half cycle switches $S_1$ and $S_4$ is turned on and during negative half cycle switches $S_2$ and $S_3$ is turned on. The optimum switching angles are generated by using this harmonic elimination strategy. The primary angles are within the first quarter cycle, the secondary angles are within the remaining three quarter cycle. Even harmonics can be eliminated if the switching pattern consists of half wave and quarter wave symmetry. By employing this control method lower order harmonics odd and triple harmonics can be eliminated. The Fourier series expansion for quarter wave symmetry can be written as follows,

$$V_n = \sum_{n=1}^{\infty} h_n \sin n\theta \qquad (5)$$

where $V_n$ represents the harmonic voltage and $h_n$ is the harmonic order

$$h_n = \frac{4V_d}{n\pi}\left(\sum_{k=1}^{N} (-1)^{k+1} \cos n\beta_k\right. . \qquad (6)$$

$\beta_k$ represents switching angle that satisfies the following equation

$$\beta_1, \beta_2, \ldots \beta_N < \frac{\pi}{2}. \qquad (7)$$

From the above equations the nonlinear equations of selective harmonic elimination can be written as follows

$$\cos\beta_1 - \cos\beta_2 + \ldots \pm \cos\beta_n = \frac{\pi h_1}{4V_d} = \frac{\pi}{4}M \qquad (8)$$

$$\cos 3\beta_1 - \cos 3\beta_2 + \ldots. \pm \cos 3\beta_n = \frac{3\pi h_3}{4V_d} \qquad (9)$$

$$\cos 5\beta_1 - \cos 5\beta_2 + \ldots \pm \cos 5\beta_n = \frac{5\pi h_5}{4V_d}. \qquad (10)$$

These nonlinear equations have to be solved offline for calculating the optimum switching angles of the multilevel inverter ($\theta_1$, $\theta_2$, $\theta_3$...$\theta_s$) for various modulation index.

## 5. SIMULATION RESULTS ANALYSING THE EFFECT OF ACMLI BASED STATCOM

The simulation and training algorithm for ANN can be done in the working platform of MATLAB as shown in Figs. 5 and 6. The Fig. 7 shows the twenty seven level output voltage obtained by trinary based ACMLI technique with amplitude of 1 kV.

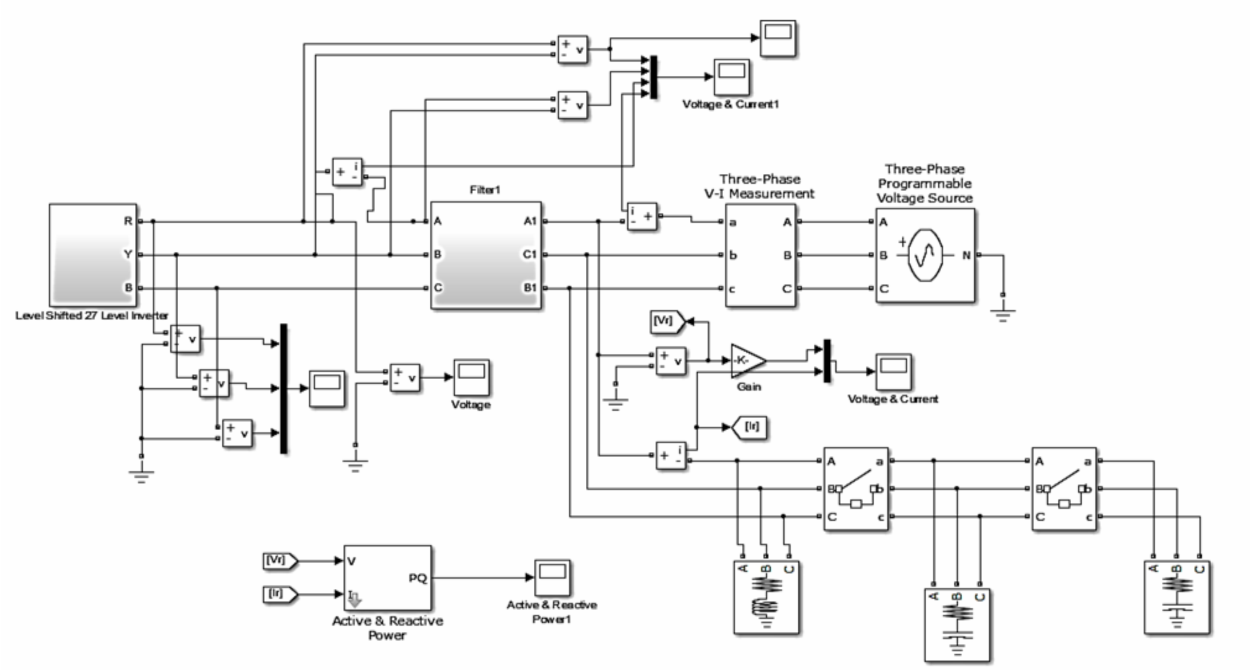


Fig. 5 – Simulation block diagram of ACMLI based STATCOM.

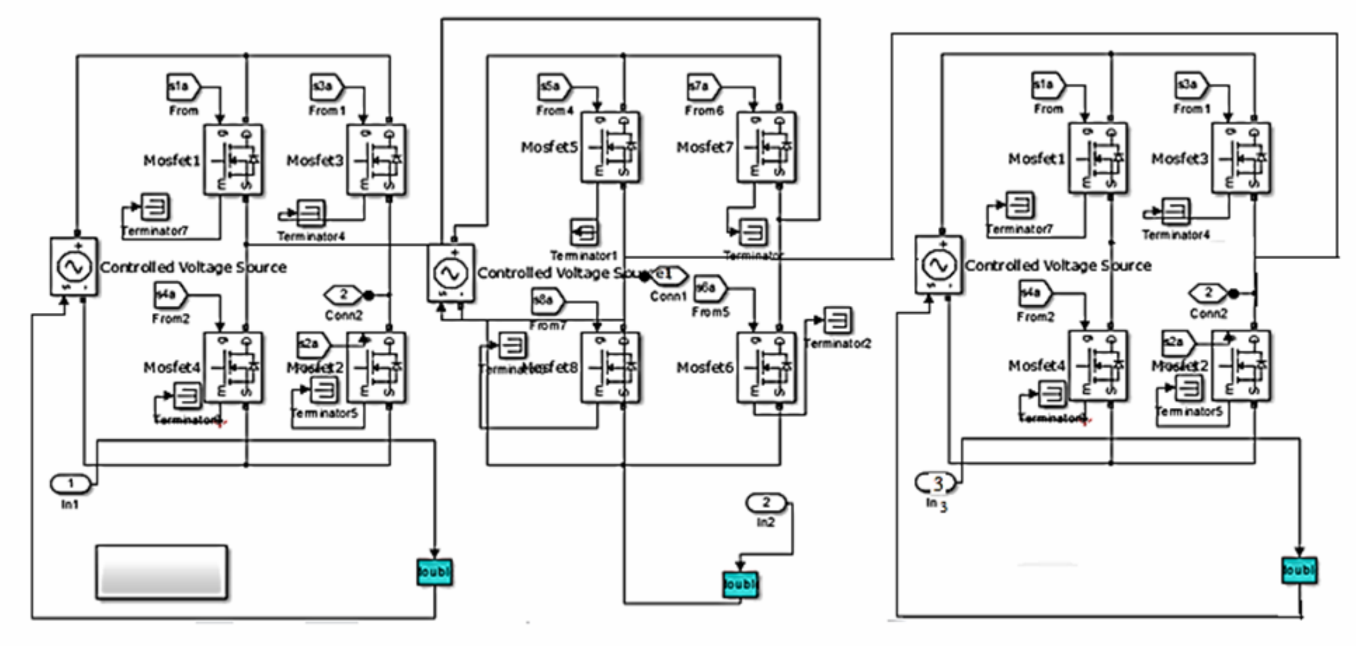


Fig. 6 – Simulation subsystem of trinary based twenty seven level inverter.

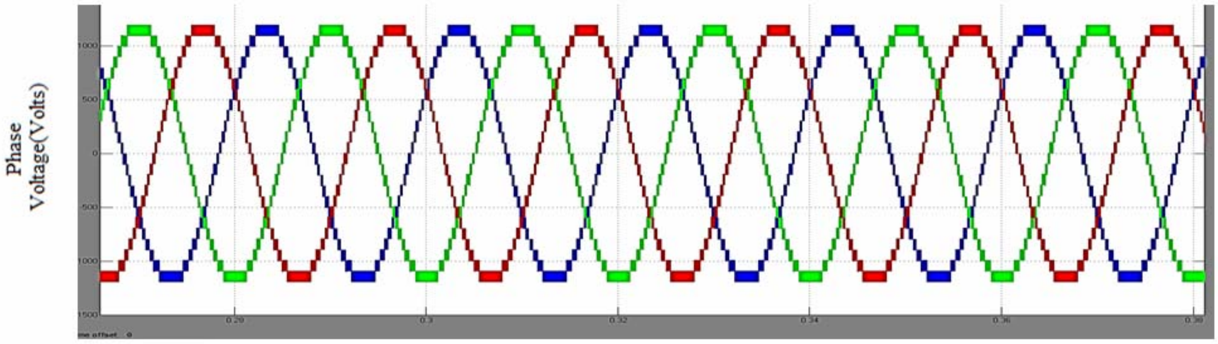


Fig. 7 – Twenty seven level three phase output voltage of asymmetrical MLI.

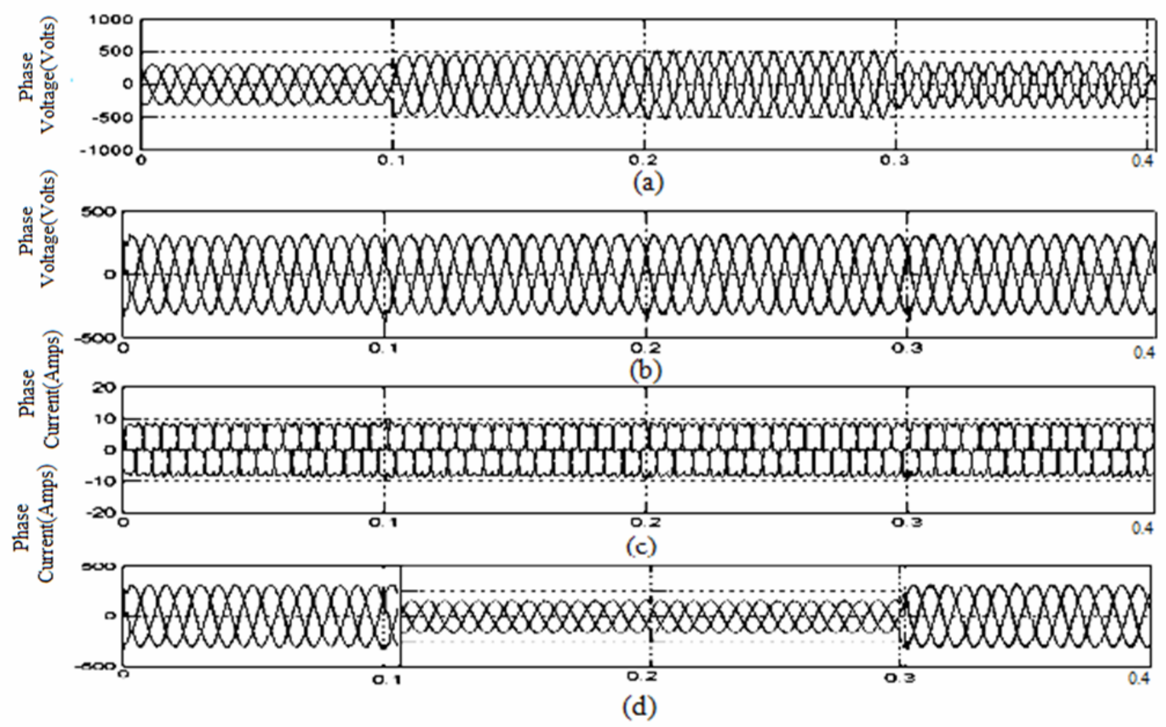
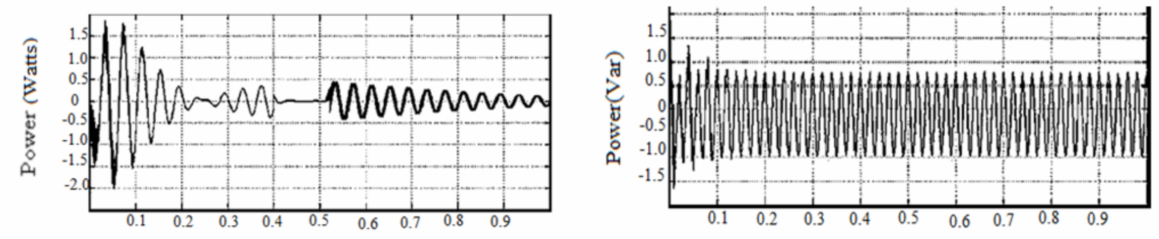
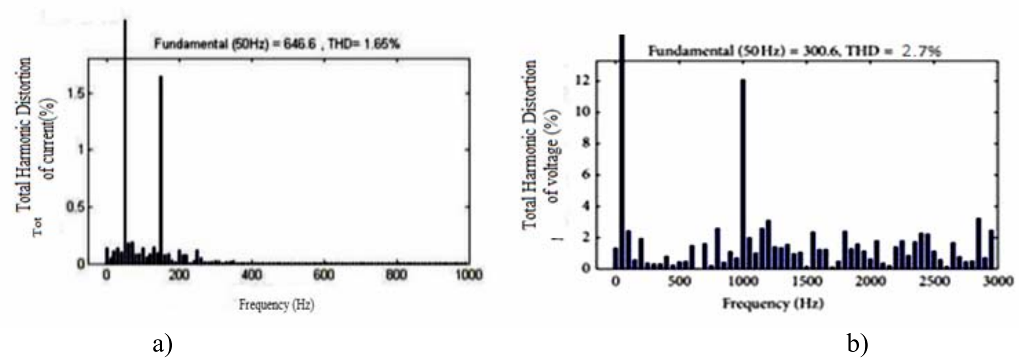


Fig. 8 – Simulation waveforms of STATCOM under unbalanced conditions ($f$ = 50 Hz, $V_{\text{lrms}}$= 12.5 kV, $I_{\text{rms (STATCOM)}}$ = 420 A, power rating = 10 Mvar); a) uncompensated three phase voltage; b) compensated three phase voltage; c) compensated three phase current; d) phase current of STATCOM.



a) b)

Fig. 9 – Performance waveforms of ACMLI based STATCOM: a) real power; b) reactive power.



a) b)

Fig. 10 – FFT analysis of inverter: a) current harmonics; b) voltage harmonics.

The performance of the system can be analyzed in MATLAB environment. The STATCOM is designed with rating of 12.5 kV, 420 A, 50 Hz. The overall simulation circuit is presented in Figs. 5 and 6 shows the three phase inverter structure with dc voltage rating of 20, 60 and 180 V. The twenty seven level output voltage of inverter is shown in Fig. 7 which is injected into the line with lower harmonic content. The FFT analysis shows 1.65%, 2.7 % voltage and current harmonics, respectively. The three phase line voltage seems to be unbalanced during the time period of 0.1 s to 0.3 s in Fig 8a. The STATCOM can be made to operate during these time periods in order to compensate it as shown in Fig 8d. The trinary voltage sequence with artificial neural controller works well with reduced harmonic content in inverter voltage. The ANN can be trained on line in order to eliminate third and fifth harmonic content which reduces the output filter requirement.

## 6. RESULTS AND DISCUSSIONS

From the results obtained it is clear that the performance of the STATCOM as well as neural network controller provides reduced harmonic content in the inverter output voltage. The Table 2 given below summarizes the THD values with ANN controller.

*Table 2*

Current and voltage harmonics with ANN controller

| *S.No* | *Switching technique* | *Total harmonic distortion* |
|---|---|---|
| 1. | Voltage harmonics with asymmetrical switching & ANN controller | 2.7 % |
| 2. | Current harmonics with asymmetrical switching & ANN controller | 1.65 % |

The third and fifth harmonics gets reduced as seen from the total harmonic distortion (THD) analysis in Fig 10. The STATCOM provides better performance in compensating serious unbalanced loads in Fig 9.

From the results the unbalanced voltage has been compensated by the STATCOM current and improves the real power transfer effectively in Figs. 8b and Fig 8d. During the time period from 0.1 s to 0.3 s the input three phase voltages are unbalanced in Fig. 8a. The STATCOM is made to operate and compensate the unbalanced load as seen from the phase current waveform of the STATCOM Fig. 8d.

The switching angles generated through ANN controller has been tabulated for various modulation indices. The ANN controller with its back propagation algorithm predominantly reduces the harmonic voltages.

## 7. CONCLUSION

This research article deals with a static synchronous compensator system which has been adopted for efficient reactive power compensation based on multilevel inverters. The CHB multilevel inverter provides reduced number of switching devices as compared with other MLI topologies. Asymmetrical switching with trinary dc sources has been used in order to develop higher number of voltage levels with reduced number of H-bridges.

An artificial neural network controller with selective harmonic elimination technique provides suppression of third and fifth harmonic voltages and effectively reduces the total harmonic distortion in the inverter output voltages. A nine level neural network controller based STATCOM system provides the advantages of reduced number of switching devices, higher output voltage levels and improved harmonic performance.

*Received on January 21, 2017*

## REFERENCES

1. L. Gyugyi, *Dynamic compensation of AC transmission line by solid state synchronous voltage source*, IEEE trans. Power, Deliv, **9**, *2*, pp. 904–911 (1994).
2. F.Z. Peng, J.S. Lai, J.W. Mckeever, J. Vancoevering, *A Multilevel voltage source inverter with separate DC sources for static VAR generation*., IEEE Trans. Ind. Appl, **32**, *5*, pp. 1130–1138 (1996).
3. J.D. Ainsworth, M.Davies, P.J Fitz, K.E. Owen, D.R. Trainer, *Static VAR compensator (STATCOM) based on single phase chain circuit converters*, IEEE Proc. Gener. Transm. Distrib., **145**, *4*, pp. 381–386 (1998).
4. C.K. Lee, J.S.K Leung, S.Y.R Hui, H.S.H Chung, *Circuit level comparison of STATCOM Technologies*, IEEE Trans. Power. Electron, **18**, *4*, pp. 1084–1092 (2003).
5. N. Hatano, T. Ise, *Control scheme of cascaded H-bridge STATCOM using zero-sequence voltage and negative-sequence current*, IEEE Trans Power Del., **25**, *2*, pp. 543–550 (2010).
6. Q. Song, W. Liu, *Control of a cascade STATCOM with star configuration under unbalanced conditions*, IEEE Trans. Power Electron., **24**, *1*, pp. 45–58 (2009).
7. R. Sternberger, D. Jovcic, *Analytical modeling of a square-wave controlled cascaded multilevel STATCOM*, IEEE Trans. Power Del., **24**, *4*, pp. 2261–2269 (2009).
8. C. Silva, *A novel modulation technique for a multilevel hybrid converter with floating capacitors,* Proc. 36th IEEE Ind. Electron. Soc. Annu. Meet., 2010, pp. 296–302.
9. S. Mekhilef, M.N. Abdul Kadir, *Voltage control of three-stage hybrid multilevel inverter using vector transformation*, IEEE Trans. Power Electron., **25**, *10*, pp. 2599–2606 (2010).
10. F. Nami, A. Zare, Ghosh, F. Blaabjerg, *A hybrid cascade converter topology with series-connected symmetrical and asymmetrical diodeclamped H-bridge cells*, IEEE Trans. Power Electron. **26**, *1*, pp. 51–65 (2011).
11. Y. Zhao, X. Han, C. He, Tan, J. Cheng, R. Zhao, *Multilevel circuit topologies based on the switched-capacitor converter and diode-clamped converter*, IEEE Trans. Power Electron., **26**, *8*, pp. 2127–2040 (2011).
12. C.K. Lee, J.S.K Leung, S.Y.R Hui, H.S.H Chung, *Circuit level comparison of STATCOM Technologies,* IEEE Trans. Power. Electron, **18**, *4*, pp. 1084–1092 (2003).
13. Y.S Lai, F.S Shyu, *Topology for hybrid multilevel inverter*, IEEE Proc., Electr. Power. Appl., **149**, *6*, pp. 449–458 (2002).
14. A.J. Watson, P.W. Wheeler, J.C. Clare, *A complete harmonic elimination approach to DC link voltage balancing for a cascaded multilevel rectifier,* IEEE Trans. Ind. Electron., **54**, *6*, pp. 2946–2953 (2007).
15. V. Kus, P. Drabek, Tereza Josefova, *Education strategy regarding the electromagnetic compatibility at low-freqeuncy*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **61**, *1*, pp. 48–52 (2016).
16. V. Kus, Tereza Josefova, *Study of the input current harmonic distortion of voltage–source active rectifiers,* Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **62**, *2*, pp. 185–191 (2017).
17. F.Z. Peng, J.S. Lai, J.W. McKeever, J. VanCoevering, *A multilevel voltage-source inverter with separate DC sources for static var generation*, IEEE Trans. Ind. Appl., **32**, *5*, pp. 1130–1138 (1996).
18. R. Shalchi Alishah, D. Nazrapour, S.H.Hosseini, M. Sabahi, Reduction of Power Electronic Elements in Multilevel Converters using a New Cascaded Structure, IEEE Trans. Ind. Electron., **62**, *1*, pp. 256–259 (2015).
19. M. Ramya, P.Usha Rani, Artificial neural network controller based nine level for STATCOM, International Journal of Printing Packaging and Allied Sciences., **4**, *5*, pp. 3232–3238 (2016).