International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 10, No. 3, Sep 2019, pp. 1437~1445
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v10.i3.pp1437-1445

Transmission system regularization with 5-level cascaded IPFC

Sridhar Babu Gurijala, K S Srikanth, Ramchandra Nittala, G. Rohit Reddy
Koneru Lakshmaiah Education Foundation, India

Article Info

Article history:

Received Oct 28, 2018
Revised Jan 11, 2019
Accepted Mar 29, 2019

Keywords:

Cascaded 5 Level Inverter
Inter Line Power Flow Controller (IPFC)
PV module
SPWM
SVM

ABSTRACT

In recent years, there is an immensely huge demand to power due to industrialization and modernization, butcorrespondingly the amplification of generation and transmission has not been done due to constrained resources and environmental limitations. The huge growth in demand lead to various problems in power systems. Heavy growth in semiconductor technology made power electronics play a key role in solving these problems. Flexible AC transmission system (FACTS) devices are used for fixing various problems in power system. They are used for enhancing the existing transmission capabilities and improving the system dynamic performance so that to make transmission system flexible and efficient in operation. Inter line power flow controller (IPFC) is a latest generation series connected FACTS device, having capability of controlling power flow among multi line in a transmission network. In this paper cascaded 5 level inverter is used as the inverter module for IPFC. Control techniques play a vital role in power flow control in the system, with the main objective of minimization of harmonics and obtaining a variable output with maximum fundamental component. This paper discusses various comparative case studies on IPFC with cascaded 5 level inverter using SPWM and SVM control techniques.

Corresponding Author:

Sridhar Babu Gurijala,
Koneru Lakshmaiah Education Foundation,
Greenfields, Vaddeswaram, Guntûr (dt), Andhra Pradesh, India. 522502
Email: sridharbabu16@gmail.com

1. INTRODUCTION

Modern bulk power systems, industries and technology are increasing rapidly day by day, so there is a huge demand to electricity. To meet the load and increasing market demand either the generation capacity should be increased or new transmission lines are to be installed or use the existing transmission system efficiently. But installation of new system deals with huge investment and takes time. Hence the utilities are forced to depend onalready existing system. In order to improve the efficiency of the system they are made to work at their maximum limit, this results in outages of lines or other equipment or could result in failure of entire system. Flexible AC Transmission Systems (FACTS) devices become an important and effective option for such increasing demand and stress on the system. FACTS devices are used in solving many issues related to transmission systems. The main function is to control power flow in transmission lines, and the other functions are voltage control, transient stability improvement and oscillation damping [1]. FACTS technologies offer better solutions in today's power systems like increasingpower transfer capability, maintaining continuous control over voltage profile, improve system damping, minimizingsystem losses, etc.

IPFC is one of the latest generation FACTS controller used to control power flows among multiple transmission lines. This device uses controllers in order to control power among the lines. Any type of converter can be used here cascaded H bridge inverter was implemented. These controllers are controlled by using control techniques, there are several control techniques, among them sinusoidal pulse width modulation (SPWM) and space vector modulation (SVM) are chosen. Details and implementation of controller and control techniques are discussed in following sections.

2. IPFC

The latest generation FACTS devices perform multiple operations which made them powerful in controlling transmission systems. UPFC is one of the versatile tool, but UPFC controls only single line at a time. The latest generation FACTS device IPFC, has the advantage of UPFC and alsoit can simultaneously manage and control power flow of multiple lines. IPFC helps in increasing the power transfer capability, regulating and managing the power flow, compensation of reactive power, preventing the loop current, and avoid the overloading of the network. In addition to these capabilities it improves voltage stability, dynamic and transient stability all these capabilities have made this tool as a multifunction device [4-6].In other words, IPFC provides highly effective scheme for power transmission management through multiline [7]-[8]

2.1. Mathematical modelling of IPFC

Rating of IPFC is specified mainly by two quantities: primarily on the amount of maximum injected voltage and secondly on the volt-ampere rating. IPFC reaches its rated power only when both the injected voltage and line current are at rated values. Power injection into lines depends on the actual power flow in the line (without any injection). Which will be seen clearly in the analysis of IPFC design.

2.2. Power injection model of IPFC

Power injection model is the Mathematical model for IPFC (Figure 1). Which helps in understanding the impact of IPFC on power system. Furthermore by mathematical modelling, IPFC can easily be incorporated in the system.

IPFC provide reactive compensation of each line independently, for effective operation of IPFC, Mathematical modeling of important components of IPFC is very essential.

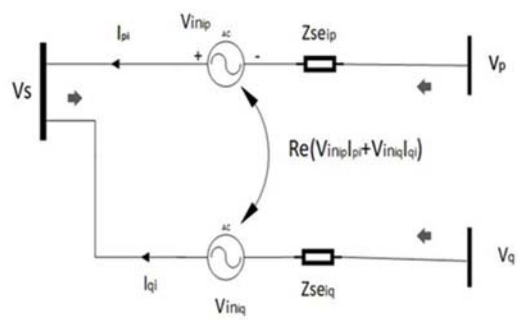


Figure 1. IPFC Power injection model

Simple design of IPFC base on our system

$$V_{in_{im}} = V_s - V_m \tag{1}$$

The amount of active power and reactive power injected into the system is calculated by the following;

$$P_{in_{im}} = \sqrt{3} V_{in} I_l \cos\phi \tag{2}$$

$$Q_{in_{im}} = \sqrt{3} V_{in} I_l \sin\phi \tag{3}$$

3. CASCADE 5 LEVEL INVERTER

This topology of inverter uses less number of switches when compared to other and soft switching is possible by new switching methods. In a cascaded H bridge inverter when L number of bridges are cascaded in a phase then the number of output voltage levels is given by 2L+1 and voltage step of each level is given by Vs/2L. The following table represents the switching mechanism for cascaded 5 level inverter (Figure 2).

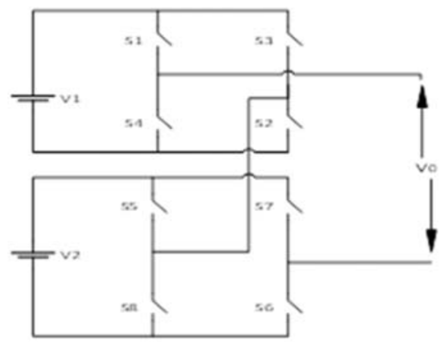


Figure 2. Cascade H bridge

Each inverter level can generate five different voltage outputs, +2Vs,+Vs, 0 and –Vs, -2Vs by connecting the DC source to the AC output by different combinations of the four switches as a shown in Table 1. Switches S1, S2, S3, S4, S5, S6, S7, and S8 are switched in different modes of switching sequences to generate output voltages across output terminals of the H bridge module. Table 1 shows the possible switching state to produce a 5-level output voltage.

The major applications of this inverter involve motor drives, electric vehicle drives, active filters, power factor compensators, interfacing with renewable energy sources

Table 1. Switching sequence of cascade 5 level inverter

output	Switching states							
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$+V_s$	1	0	0	1	1	1	0	0
$-V_s$	0	1	1	0	0	0	1	1
0	0	0	0	0	0	0	0	0
$+2V_s$	1	0	0	1	1	0	0	1
$-2V_s$	0	1	1	0	0	1	1	0

4. PV MODULE

Solar electric power generation system generates electricity when solar radiation is penetrated through solar module. A number of solar cells connected in series based on required standard output voltage and power. The rating of PV modules is done with their output open circuit voltage V_{OC} , short circuit current I_{SC} , peak power W_P . In this paper we are using PV module as a DC link, to maintain the voltage on DC side. The line diagram of PV module is shown in figure.

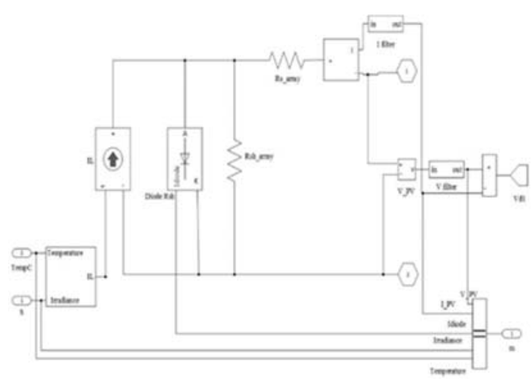


Figure 3. PV module line diagram

5. CONTROL TECHNIQUES

Control system plays a vital role in controlling the injected voltage or power from IPFC. Control techniques are important because converters output consists of fundamental frequency component along with different frequency components, such frequency components are undesirable to the system and they are responsible for operational imperfections at various levels.

Hence employing of suitable control techniques for multi-level inverter to operate over wide range of loading conditions with less THD percentage and obtaining of higher converter efficiency has been a topic of intensive research.

The main objectives of modulation strategies are:

a. Capable of operating over wide ranges of modulation index, Less THD output voltage, less switching losses, Easy for implementation, time and computational burden should be less.
b. Various methods have been developed, a survey of modulation methods is given in [9]. Various algorithms and approaches of triangular comparision (TC) and space vector (SV) were discussed in [10], [13].

6. SPWM

SPWM stands for Sinusoidal pulse width modulation. It is adapted for reductioninharmonic content in output voltage and obtainingsinusoidal output. Implementation of this is easy and several studies were done [24]. The gate pulses are generated when sinusoidal reference signal is compared with rectangular carrier wave.

The output frequency of the inverter can be calculated when frequency of the reference wave is known. In order to calculate the output voltage of the invertermodulation index is used and this modulation index is controlled by peak amplitude.

Some of the advantages of SPWM are;

a. The output voltage is near sinusoidal.
b. Reduction in harmonic content in the output voltage.

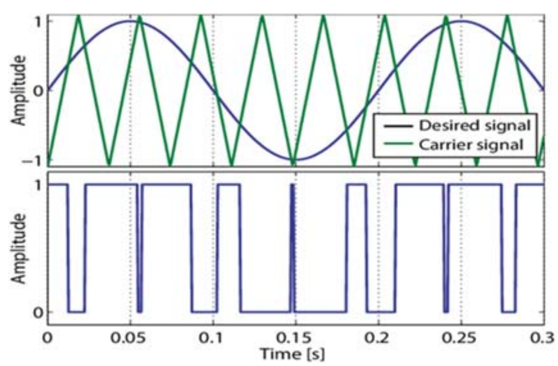


Figure 4. Generation of pulses by SPWM

7. SVW

The development in digital signal processors lead to the implementation of various PWM methods have become popular, of these methods SVPWM have become one of the most popular PWM methods [11]-[12]. Duty cycles are important in obtaining required output, it uses space vector (SV) approach in order to compute duty cycles for switches. A simplified approach of SVPWM was proposed in [14]-[16].

A three phase inverter generates 8 switching states of these 6 are active states and 2 are zero states. Six sectors spanning 600 each form a hexagon. A combination of switching states and by maintaining volt-second balance generates reference voltage space vector V_{ref} .

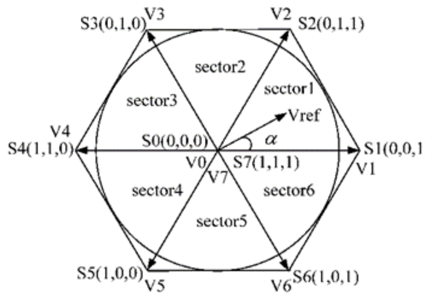


Figure 5. SVM sectors

It is produced in average sense as there is no direct way to generate this.In order to obtain sampled reference vector in terms of magnitude and angle, the produced voltage vectors are applied at different durations within a sampling time period such that average vector produced over a sub cycle is equal to sampled reference vector.

7.1. Calculation of reference vector V_{ref}

$$V_d = V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn} \tag{4}$$

$$V_q = \frac{\sqrt{3}}{2}V_{bn} - V_{cn} \tag{5}$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \tag{6}$$

$$\therefore V_{ref} = \sqrt{V_d^2 + V_q^2} \tag{7}$$

And

$$\alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) \tag{8}$$

7.2. Determination of switching time duration

$$T_1 = \frac{\sqrt{3}.T_z.\left|V_{ref}\right|}{V_{dc}}\left(\sin\left(\frac{n}{3}\pi - \alpha\right)\right) \tag{9}$$

$$T_2 = \frac{\sqrt{3}.T_z.\left|V_{ref}\right|}{V_{dc}}\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right) \tag{10}$$

$$T_0 = T_z - T_1 - T_2 \;\; Where \;\; T_z = \frac{1}{f_z} \tag{11}$$

A circular trajectory is formed inside hexagon in sinusoidal reference space vector form. In SVM, the radius of largest circle that can be inscribed within hexagon is the highest possible voltage that can be achieved. The maximum obtainable fundamental output voltage is.

$$\left|\overline{V_{ref}}\right| = \frac{2}{3}V_{dc}\cos\frac{\pi}{6} = \frac{1}{\sqrt{3}}V_{dc}$$

When compared to SPWM, SVM is having maximum DC bus utilization. There are a number of publications describing the various aspects of SVM for high level inverters [19]-[23].

8. CASE STUDIES

The system is designed byconsidering a source point (sending end) at 33kv. R1, R2 and XL1, XL2 are the transmission line parameters. Since most of the industries take 11kv, T1 and T2, step down transformers are used which steps down 33kv to 11kv. As IPFC is a back to back connection of voltage source converters. VSC 1 and VSC 2 are the two voltage source converters. The DC sides of these converters are connected with a common DC link. Here PV module is used as a DC link. Load 1, 2, 3, 4 are considered as industrial loads. In order to test the efficiency of control techniques incorporated, in IPFC, there are two case studies considered.

a. Voltage drop at the receiving end of transmission line
b. Sudden load on both the transmission lines

In both the cases, IPFC is connected to the testsystem with two control techniques individually. The pulses are given to cascaded h bridge inverter through two control techniques. Finally a comparative analysis is drawn between the control techniques incorporated in IPFC with cascaded inverter. The above case studies are performed and the best possible control technique is investigated.

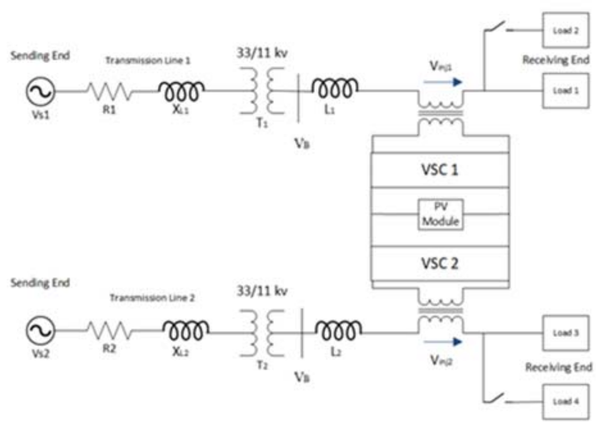


Figure 6. Line diagram of IPFC

8.1. Voltage drop at the receiving end voltage of transmission line

When 11kv is being transmitted through line, due to heavy inductive nature of load in the receiving end we have absorbed a huge drop in the receiving end voltage. The voltage has been dropped from 11kv to 5kv in both the transmission lines. This drop affects the generation side and in turn the generation capacity should be increased in order to compensate the drop. In order to improve this scenario we have implemented IPFC in the system. We have incorporated IPFC as shown in Figure 6.

Figure 8 represents voltage at receivingend of line1 with IPFC-SPWM, when IPFC-SPWM is incorporated it is observed that the voltage has been improved to 11kv. The same is observed in line 2. Figure 9 represents voltage at receivingend of line1 with IPFC-SVM. On comparison of both these figures, it is seen that initially the voltage with SPWM is being accumulated with harmonics. The THD with IPFC-SPWM is 6.20% where the THD with IPFC-SVM is 0.15%.

Figure 10(a) represents RMScurrent at the end of transmission line1 with IPFC-SPWM and figure 10(b) represents current with IPFC-SVM. In comparison the RMS current with IPFC SPWM is 5A whereas with SVM it is 9A. With SPWM initially till 0.04s harmonics are seen but in case of SVM they are absent. THD with SPWM is 8.68% and with SVM it is 0.14%.

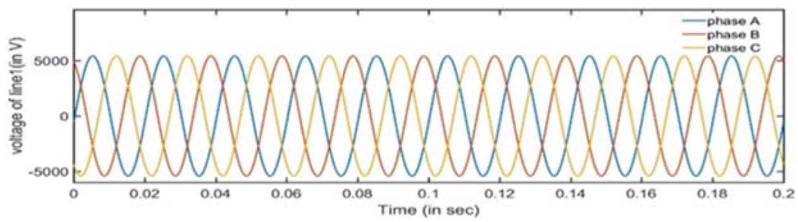
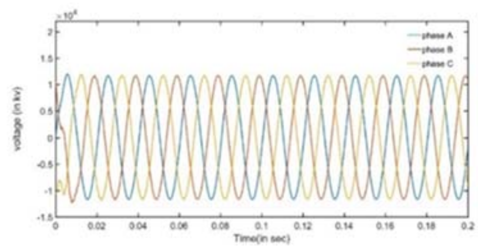


Figure 7. Voltage at transmission line 1 in the absence of IPFC



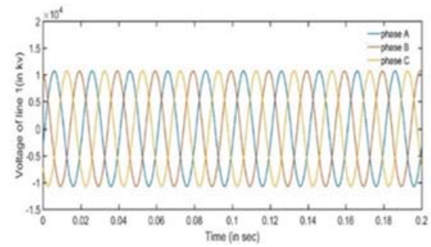
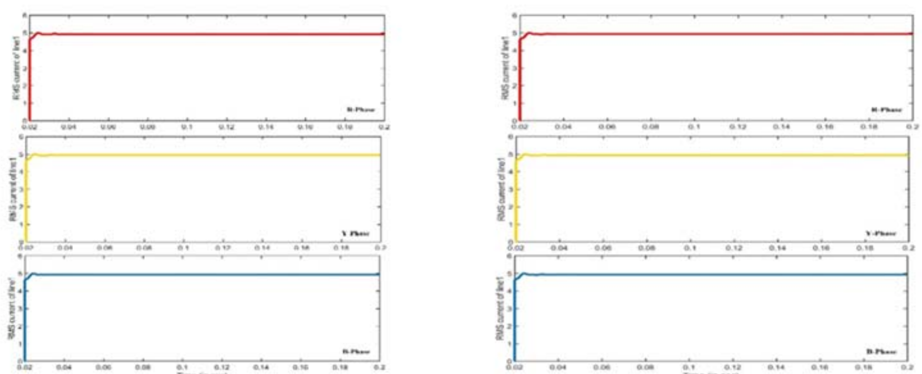


Figure 8. Voltage in the presence of IPFC-SPWM Figure 9. Voltage in the presence of IPFC-SVM



(a) (b)

Figure 10. (a) RMS current of line 1in presence of IPFC-SPWM (b) RMS current in presence of IPFC-SVM

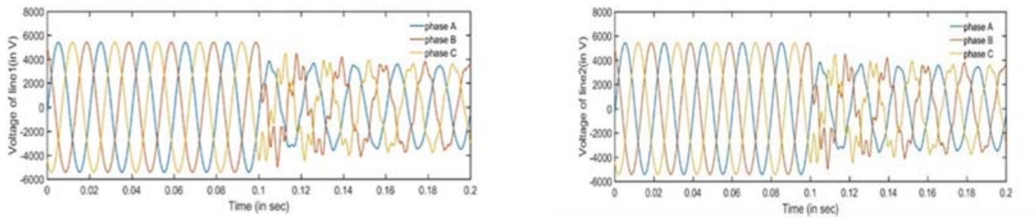
8.2. Sudden increase in load on both transmission lines

In this case both the lines at the receiving end has undergone with a sudden addition of load at 0.1sec at same instance of time. Figure 11 represents receiving end voltage of both transmission line. In both the lines it is observed that voltage has dropped from 5500V to almost 2800V when the load is added suddenly the voltage is completely distorted.

From Figure 12 it is observed that voltage with both control techniques is very well compensated by IPFC. Similar to case 1 the major difference in the control techniques is observed in terms of receiving end current and THD values. THD of IPFC-SPWM is 6.19% and that of IPFC-SVM is 0.15%.

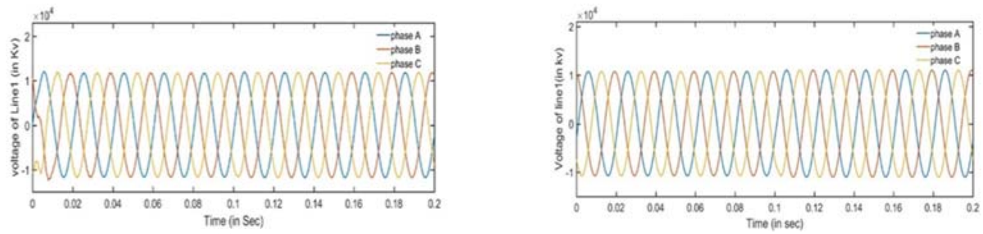
Figure 13 (a) represents RMS current of line1 in presence of SPWM and (b) represents in presence of SVM. In this case since there is a sudden increase in load at 0.1s there is a small disturbance seen. And in SPWM RMS current has harmonics in the beginning.

In IPFC-SPWM THD is 8.66% and with SVM it is seen as 0.14%. Hence observing these two cases SVM is proven as optimum solution in terms of voltage compensation. Therefore for an IPFC with cascaded H bridge inverter SVM control technique is the optimal solution for transmission line problems.



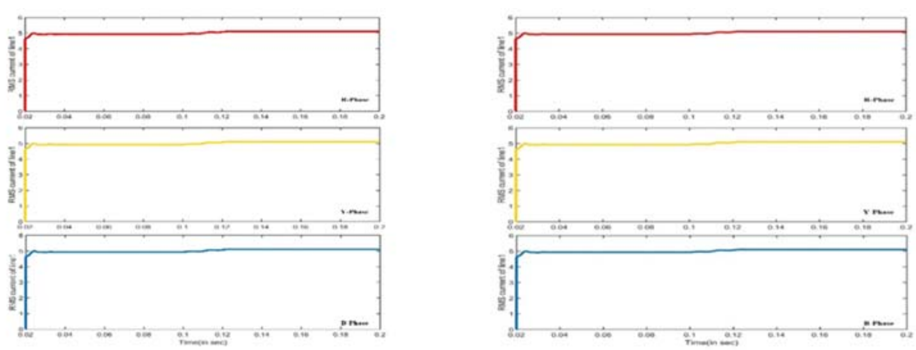
(a) (b)

Figure 11. (a) & (b) Voltage at line 1 and line 2 when there is a sudden increase in load



(a) (b)

Figure 12. (a) Voltage at the of line 1 in presence of IPFC-SPWM, (b) in presence of IPFC-SVM



(a) (b)

Figure 13. (a) RMS current of line 1 in presence of IPFC-SPWM (b) RMS current in presence of IPFC-SVM

Table 2. THD values of all case studies

cases	Voltage THD with IPFC-SPWM	Voltage THD with IPFC-SVM	Current THD with IPFC-SPWM	Current THD with IPFC-SVM
Dropping of the receiving end voltage of Tr.line1	6.20%	0.15%	8.68%	0.14%
Sudden increase in load on two Tr.lines	6.19%	0.15%	8.66%	0.14%

9. CONCLUSION

In this paper a comparative analysis is performed on the control techniques of IPFC with different case studies. Control technique is the basic building block of IPFC, so choosing a proper control technique is a challenging task. From the results obtained in the above case studies it is evident that the best solution for power flow control if IPFC, in case where more than two lines are emerging. From the case studies performed above it is observed that though IPFC with SPWM is maintaining good voltage profile, IPFC-SVM is maintaining good fundamental component along with good voltage profile and less THD, which is satisfying the objective of a control techniques.

REFERENCES

[1] J. Guo, M. L. Crow and JagannathanSarangapani, "An Improved UPFC Control for Oscillation Damping", *Journal of IEEE Transactions on Power Systems*, Vol.24, No.1, pp.288-296, February 2009.

[2] N. Abi-Samra, D. Camovale, A. Sundaram, W. Malcolm, "The role of the distribution system dynamic voltage restorer in enhancing the power at sensitive facilities," *WESCON/96*, Page(s): 167 -181, 1996.

[3] R. Buxton, "Protection from voltage dips with the dynamic voltage restorer," *IEE Half Day Colloquium on Dynamic Voltage Restorers - Replacing Those Missing Cycles, Glasgow*, 1998, pp: 3/1 -3/6. (Digest No. 1998/189)

[4] A. Burden, "Caledonian Paper DVR-the utility perspective," *IEE Half Day Colloquium on Dynamic Voltage Restorers - Replacing Those Missing Cycles*, Glasgow, 1998, pp. 2/1-2/2. (Digest No. 1998/189).

[5] J Chen, TT Lie "Enhancement of power system damping using VSC based series connected FACTS controllers" _ *Distribution, IEE*, 2003

[6] R Strzelecki, J Bojarski- "Probabilistic method for parallel filter's power selection in interline power flow controller*" EPE-PEMC Conference*, Citeseer, 2002.

[7] MR BANAEI "Improvement of Dynamical Stability Using Interline Power Flow Controller" - *Advances in Electrical and Computer* , 2010

[8] L. Gyugyi, K. K. Sen, and C. D. Schauder, "The interline power flow controller concept a new approach to power flow management in transmission systems," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1115–1123, Jul. 1999.

[9] N.G. Hingorani and L. Gyugyi. Uniderstanding FACTS-Concepts and Technology of Flexible AC Transmission Systems. IEEE press, First Indian Edition, 2001.

[10] R. Palanisamy, K. Vijayakumar, D. Selvabharathi "MSPWM based Implementation of Novel 5-levelInverter with Photovoltaic System" IJPEDS volume 8, No 4, December 2017.

[11] Grahamme Holmes and T.A. Lipo, "Pulse width modulation for power converters" IEEE press, 2004.

[12] Debanjan Roy, Madhu Singh, Tapas Roy "A Novel Approach for Space Vector Based PWM Algorithm for Diode Clamped Three level VSI Fed Induction Motor Drive". *International Journal of power Electronics and Drives (IJPEDS),*, Volume 8, No 4, Dec 2017.

[13] P.G. Handley and T.J. Boys, "Space vector modulation: An engineering review" *IEE 4th International Conference on Power Electronics and Variable Speed Drives*, *Conf Pub* 324, pp. 87-91, 1990.

[14] G. Narayanan and V.T. Ranganathan, "Triangle comparison and space vector approaches to pulse width modulation in inverter fed drive", *Journal of Indian Institute of Science*, Sept/Oct, pp. 409-427, 2000.

[15] Joohn-Sheok Kim and Seung-Ki Sul, "A novel voltage modulation technique of the space vector PWM" in *Proc. IPEC*, Yokohama, Japan, pp. 742-747, 1995.

[16] Dae-Woong Chung, Joohn-Sheok Kim and Seung-Ki Sul, "Unified voltage modulation technique for real-time three-phase power conversion" *IEEE Trans. Ind. Applicat*., vol. 34, no. 2, Mar/Apr, pp. 374-380, 1998.

[17] T. Brahmananda Reddy, J. Amarnath and D. Subbarayudu, "Improvement of DTC performance by using hybrid space vector Pulsewidth modulation algorithm" *International Review of Electrical Engineering*, Vol.4, no.2, Jul-Aug, pp. 593-600, 2007.

[18] Stephen W. Middlekauff, E. Randolph Collins, Jr., "System and Customer Impact: Considerations for Series Custom Power Devices," *IEEE Trans. On Power Delivery*, Vo1.13, No.1, Jan, pp. 278-282, 1998.

[19] Amit Kumar Gupta and Ashwin M. Khambadkone, "A General Space Vector PWM Algorithm for Multi Level Inverters, Including Operation in Overmodulation Range", *IEEE Transactions on Power Electronics*, vol. 22, no. 2, March 2007.

[20] B. Sirisha, P. Satish Kumar, N.Susheela, "Three Phase Two Leg Neutral Point Clamped Converter with output DC Voltage Regulation and Input Power Factor Correction", *International Journal of Power Electronics and Drive System (IJPEDS)*, vol. 2, no. 2, June 2012.

[21] B. Sirisha, P. Satish Kumar, "A Space Vector Pulse Width Modulation Technique for Five Level Cascaded HBridge Inverter Including Over Modulation Region with FPGA Implementation", *International Journal of power Electronics and Drives (IJPEDS)*, vol. 8, no. 3, September 2017.

[22] B. Sirisha, P. Satish Kumar, "Implementation of FPGA based Space Vector PWM Methodfor Five Level Cascaded Inverter", *IEEE 7th Power India International Conference (PIICON 2016)* at Bikaner Rajasthan, November 25-27 2016.

[23] B. Sirisha, P. Satish Kumar, "A Simplified Space Vector PWM for Cascaded H- Bridge Inverter including Over Modulation Operation", *13th International IEEE India Conference INDICON 2016* at IISC, Bengaluru, India. December 16-18, 2016

[24] Nabil Farah, Jurifa Bt. Mat Lazi, MHN Talib"Comparative Study of Three Different Topologies of Five-Level Inverter withSPWM Modulation Technique" *International Journal of power Electronics and Drives (IJPEDS)*, Volume 8, No 4, Dec 2017.