Research Training Fellowship for Developing Country Scientist (RTFDCS) Report

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Duration:	3rd November 2010 to 14th March 2011
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Research Theme:	Converter Topologies with Reduced EMI/EMC Effects

1.0 Main body

This research training report details the activities undertaken by research candidate in the quest to define a researchable PhD problem in areas of modern power electronics.

1.1 Abstract of Research

Natural phenomena and advances in technology have worsened electromagnetic energy emission to the environment. This electromagnetic energy emanate from both intentional and non-intentional sources. This energy when it attains enough strength affects and interferes with the operations of most electrical and electronic equipment. Generally these effects are called electromagnetic interference (EMI) noise.

Power electronic converters are mostly either sources or victims, or both, at the same time, of the EMI noise. Stricter EMI regulations, circuit miniaturisation along with advances in semiconductor switching speeds have created difficult engineering tradeoffs for designers of power electronic equipment. Faster switching requirements on power devices in order to reduce losses and device size inherently result in increased high frequency EMI noise. This noise brings about the problem of nonconformity to electromagnetic compatibility (EMC) standards. Also, the miniaturisation happening nowadays causes power electronic converters to become susceptible to the noise they generate.

The oldest way to fight EMI has been to use filters, grounding and shielding. However, filtering has been shown to be rife with a lot of shortcomings with regards to size, weight and cost. A critical setback is due to the difficulties in understanding noise interactions between converters and filters within a system made of several converters and their filters. Also, filters will suppress part of the wanted signals. Apart from filtering, other methods which have shown remarkable noise elimination capability include confining the noise currents within a converter, optimizing the circuit parameters and cabling to reduce the existence of nodes with high voltage, reducing the voltage stress on converters during switching. Other methods include switching of converters with voltage states which allow elimination of EMI, shunting the noise currents to artificial grounds within a system, random modulation which redefines the EMI energy from narrow-band to wide-band spectrum, selecting switching frequencies with fewer distortions to the line voltages. However, there are disadvantages resulting from using these methods such as additional circuitry, complicated design and control, increasing ripple in the output, reducing efficiency of the circuit, and at higher switching frequencies will cause resonances which add to the noise content.

From this view, it is preferable to integrate the EMI noise mitigation techniques in the early design stages to avoid the foreseen problems. Also, there exists a need to identify and characterise the dominant noise emission modes in power converter application frequencies, knowledge of which will enable application of suitable corrective measures.

Within this work, an attempt has been made to review literature and perform preliminary simulation. The simulation is still going on to identify suitable modelling approaches to reduce EMI in power electronic converters. This was a pre-doctoral research problem identification program which is expected to be carried out further for pursuance of doctorate degree.

2.0 Researching Power Electronic Converters with Reduced EMI/EMC Effects

2.1 Introduction

Natural phenomena and advances in technology have increased the quantity of electromagnetic energy pollution proliferation in the environment. This electromagnetic energy emanate from both intentional and non-intentional sources. The energy has certain effects on and interferes with the operations of most electrical and electronic equipment when it attains sufficient strength [1, 2]. Broadly the effect is called electromagnetic interference (EMI) noise. The intentional sources of EMI include various apparatus such as radio and television broadcast stations, communication and radar and navigational aids. Unintentional sources include electrical appliances such as atmospheric discharges, automobile ignition systems, industrial control systems and household appliances. Figure 1 shows some of the common sources of EMI noises in the ambience.

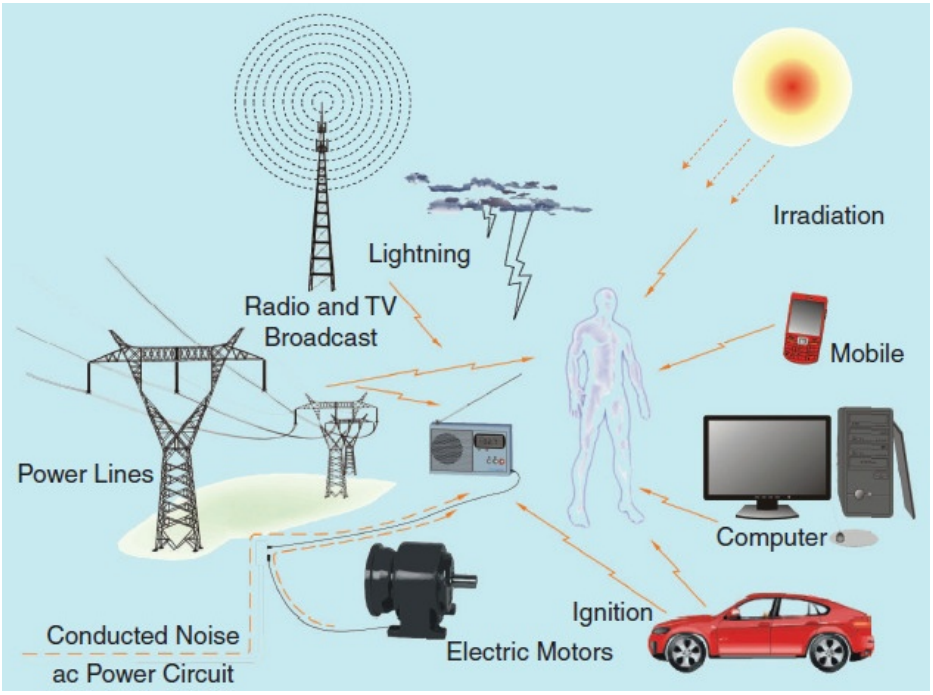


Figure 1. Typical electromagnetic environment [4].

This electromagnetic environment involves three complex electromagnetic disturbance phenomena described as: low-frequency phenomena (conduction and radiation, except electrostatic discharge); high-frequency phenomena (conduction and radiation, except electrostatic discharge); and electrostatic discharge phenomena (conduction and radiation) [15].

Development of EMI subject has been extensively developed as in [1]. From the early concerns of radio broadcasting interference with other electrical equipments, the setting up of performance standards of EMI, and the establishment of several organizations which work closely to define the limits and acceptable tolerances of emissions and susceptibility of equipments in electromagnetic environment. Few of these organizations working on EMI issues are International Electrotechnical Commission (IEC), Special Committee on Radio Interference (CISPR), Federal Communications Commission (FCC) and British Standards

Institutions (BSI). These organizations at one time or another put forward some interference limits to be met by electrical and electronic equipments. These set standards whereby equipment is not affected or does not affect others with EMI is what is termed as Electromagnetic Compatibility (EMC) standards.

Negative effects of EMI are possible malfunction or damage to the electrical and electronic systems for example semiconductor devices and VLSI circuits. In [2, 4] the negative effects of EMI are outlined, some of which are crashing of a Blackhawk helicopter due to strong radar signal, several cases of diverting flights due to usage of cell phone by passengers inside the plane thereby creating fear of interference of the plane navigation and communication systems with the phone frequencies, several cases of medical device malfunction in Canada and elsewhere e.g. RF interference causing death of a patient in ambulance, 10 MW power converters interfering with telephone lines 12 miles away. For the case of industrial drives fed with inverters, there is the problem of large noise currents circulating within the system which deteriorate the insulation and causes trip of protective relays and sometimes damages the drive system. However, this interference could be put to good use in electronic warfare technology for example radio jamming.

Power electronics converters are one of the products which need to conform to the set standards since, more than most they are either sources or victims, or both, at the same time, of the EMI noise [1 - 14]. The tightened EMI regulations along with advances in semiconductor switching speeds have created difficult engineering tradeoffs for designers of power electronic equipment. The faster requirements of power devices in order to reduce losses and device size inherently produce more high frequency noise that must be managed so that the equipment will conform to the EMC standards. Furthermore, as the equipment shrinks in size, it becomes increasingly susceptible to the noise that it generates.

2.2 EMI Sources and Coupling Paths in Electronic Power Converters

Rapid changing of magnitude and direction of voltage and/or line current are the most important EMI sources in power electronic converters, though these results from required power conversion action. The changes cause line current distortions which circulate in the line and emit EMI. EMI is separated into several types for purposes of analysis and regulation. First, EMI can be split into radiated and conducted emissions. Radiated emissions consist of electromagnetic energy that is propagated through space. Conducted emissions represent electromagnetic energy that is propagated through conductors. Second, conducted EMI is several orders of magnitude higher than radiated EMI at frequencies less than 1 GHz and it will be given the most focus in this research because most power conversion devices operate in this frequency range. Transfer of conducted electromagnetic energy occurs due to coupling paths created by reactive components i.e. inductors and capacitors as shown in Figure 2 [4, 5].

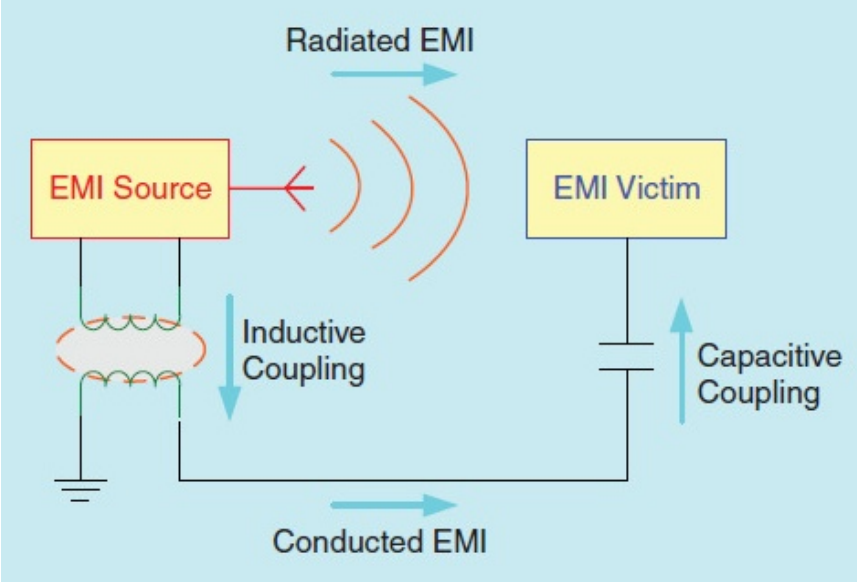


Figure 2. EMI coupling modes [4, 5]

Conducted emissions can be further partitioned into common-mode (CM) and differential-mode (DM) emissions. However, existing EMI standards do not make the distinction between common-mode and differential-mode emissions. Therefore, it is often useful to make this distinction for purpose of analysis and development of attenuation techniques [2]. CM noise is conducted through all lines in the same direction, and always exists between any power line and ground. DM noise is conducted through all lines in inverse directions, and always exists between power lines. Take example of one type of switch mode power supply (SMPS) unit, a front end PFC boost converter which in its operation generates noise whose path is depicted in Figure 3.

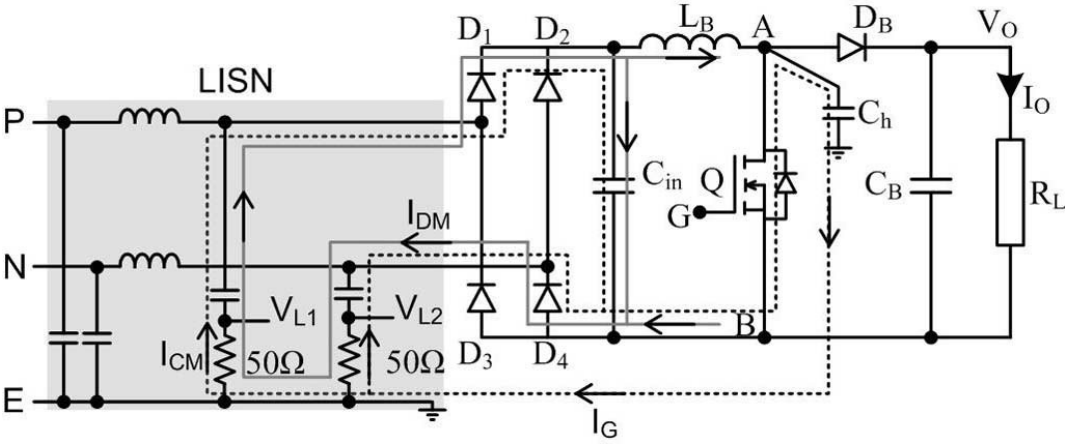


Figure 3. Front-end PFC boost converter with conducted noise paths [13]

In the figure above, the DM noise current is largely due to the normal switching (rapid changing current magnitude and direction). This current flow between the phase and neutral lines and its FFT contains harmonics. The CM noise current flows in the ground wire and returns, in phase, via both the ac lines (P and N). This noise current is typically caused by leakage (both capacitive, C_h and inductive couplings, where also the L_B contribute) occurring within the SMPS unit. In this case of a boost PFC unit, the CM noise is mainly due to the high rate of change of voltage at the drain of the switching power device.

Operation of inverters to supply motor loads is plagued with existing leakage capacitance within the converter, in the power lines, in the windings, in the rotor and stator, and between stator and ground. These lead to the flow of CM current from the motor to ground and back to converter and to the mains supply as well as accompanied DM due to the pulsating voltage and currents drawn by the converter. The CM currents in motors causes deterioration of the winding insulation, tripping of ground protection relays, and excessive bearing wear as well as aggravating the EMI emission problem [40]. Also, there is oscillating voltage pulses which are as detrimental seen at the motor terminals. This is brought about by the long cable impedance mismatching with motor terminal impedance [38].

2.3 EMC Standards

EMC standards are the performance specifications stipulated in a standard providing for the minimum requirements that a particular system will function satisfactorily within permissible design tolerances in electromagnetic environment. To this end our power electronic systems must meet the minimum EMC requirements so that the emission levels are tolerable and their immunity is accepted. Some examples of these standards are the IEC and CISPR emission limits.

It is quoted in [1] that the IEC/CISPR has divided the equipments into two broad categories known as Class A and Class B with regards to their permitted emission levels. The first are equipment for use in industrial, commercial, and business environments. The second are intended for use in domestic environments. Figure 4 presents an adaptation found in [13] of the respective limits of EMI emission levels as per CISPR 22 standards.

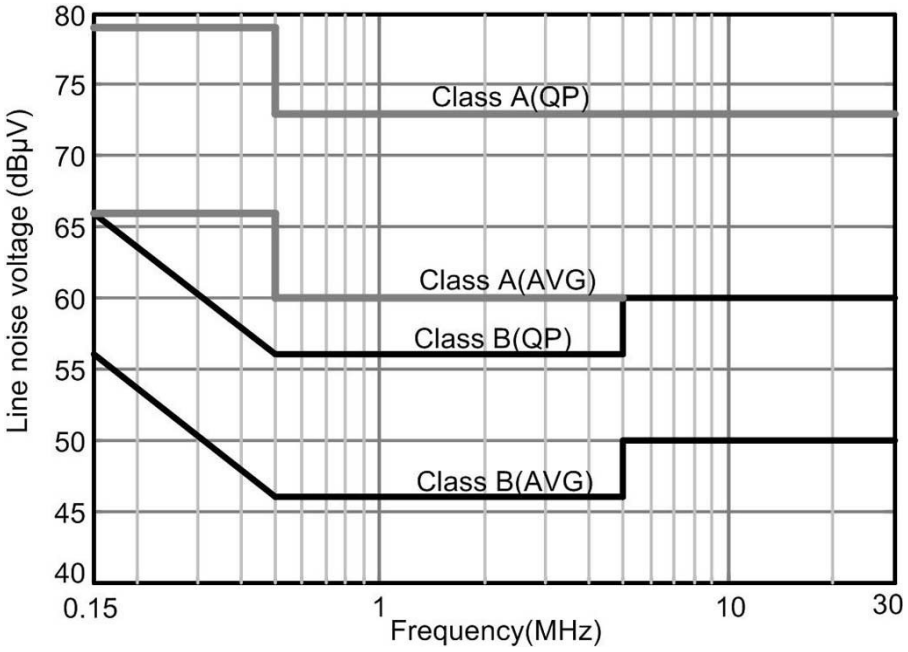


Figure 4. Conducted Emission levels as per CISPR 22 Standards found in [13]

[17] For class B equipments, the frequencies below 0.5 MHz, the permissible noise level increases inversely with frequency in approximate conformance to the atmospheric noise in the ambient. Above 0.5 MHz, the level is constant to 5 MHz where the permitted level

increases by 4 dB to allow for rise in ambient noise. For class A equipments, the permissible levels are constant up to 5 MHz and then drops by 7 dB because the ambient noise level is lower at these frequencies.

2.4 Statement of the Problem

The oldest way to fight EMI has been to use filters, grounding and shielding as explained in [1, 4, 13]. For the case of power converters, filters could be installed in the input side and output side as deemed fit. This is a separate circuit that could be designed at a later stage after product manufacture and testing, and then connected to the equipment. There are two types of filters being passive filters and active filters. For example, a hard switched inverter's CM noise could be minimised by increasing the value of the series power device gate's resistances. This is passive filtering. However this method is inferior to active filtering. Active filtering is more advantageous since it optimises its performance using a feedback loop. For example, one researcher [3], using active filtering achieved a switching loss 27% lower than when using passive filtering for a hard switched power converter.

Further, filtering has been shown to be rife with shortcomings as pointed out in these works [2-4, 6-11, 13, 14]. The drawbacks of the filtering methods are that they complicate the design of the power converter in regards to weight, size, and efficiency since they mean additional components added to the circuitry. Another setback is due to the difficulties in understanding noise interactions between converters and filters within a system made of several converters and their filters. Also, filters will suppress part of the wanted signals. From manufacturing point of view [1, 2], it is better to integrate the EMI noise mitigation technique in the early stages rather than leave it for later stages where cost implications will be high and the product could be obsolete and impact on wasting man-hours. Furthermore, the challenge is to identify which are the dominant emission modes in certain application frequencies [39] which will enable application of suitable corrective measures.

2.5 Objectives of the Research

2.5.1 Main Objectives

The preceding discussions have showed what are the sources, paths, effects and existing methodologies used to mitigate EMI in power converters. As such, this work intends to investigate two issues namely suitable design and control strategies which will reduce EMI in power converters. The work is compartmentalized in the research questions posed below.

2.5.2 Specific Objectives

This research will specifically try to answer the following questions:

1. How to model physical topologies that eliminate or reduce the leakage capacitance and inductances within a converter? [22, 20, 25, 24, 21, 23, 27, 4, 29, 28, 19].
2. How to use space vector modulation techniques with how many inverter levels to use in AC drives to reduce the leakage capacitances existing within the inverter, between the power lines, between the windings, stator and rotor, and between the system and ground taking into account the effects of long motor cables? [20, 34, 35, 36, 30, 32, 31, 38].
3. How to effectively employ randomized modulation control techniques of converters to reduce the EMI energy, reduce the leakage capacitances and inductances without opening the converter? [23, 13, 21, 26, 4, 9, 29, 28, 19, 18].

4. How to model the high frequency AC machine fed by inverter depicting all leakage capacitances, inductances, skin and proximity effect of cables and all couplings with aim of finding a method to cancel them? [22, 27, 31, 39, 37].

2.6 Literature Review on Existing Methods to Manage EMI and Their Shortcomings

Literature has proposed several methods to suppress EMI in power converters which include: improvements on the layout of components and forcing the diode bridge to operate in continuous conduction mode so as to reduce harmonics [7]; using a compensating transformer winding and a capacitor [14]; auto-tuning systems/boards to effectively select switching modes with less distortions of the current/voltage [8]; dithering of switching frequency to spread the EMI energy over limited frequency range [6]; soft switching so as to reduce the switching voltage [10, 11]; randomising the modulation action [4, 9]. One such random modulation is chaos control strategy which results in spreading the narrow band frequency EMI energy to a broad band frequency [4, 9]. Further, with space vector modulation control, it is possible to switch the converter with states that results in elimination of either CM or DM [20, 34, 35, 30, 32, 38]. In [7] there is considerable reduction in harmonic current level, and maximum power transfer occurs with improved power factor in the continuous conduction mode. Passive cancellation presented in [14] managed to reduce the choke requirement for the filter, gate drive circuits, and no additional transistors. The compensation winding conducts only the noise currents due to it being shunt connected to the power current flow. The work in [8] achieves optimal converter assembly configuration. Its auto-tuning board enable selection of converter switching frequencies which produce low disturbances on the control signals and achieve self internal compatibility. The pseudo-random dithering of the switching frequency achieves EMI reduction by virtue of spreading the noise signal frequency into broad band [6]. This method requires only software changes whereby it converts specific long-wave range narrow band into broad band noise wave [6]. Soft switching technique of [10, 11] achieves less transients on the switching waveforms resulting in less conducted EMI. Possible combination of random variation of the switching frequency, delay coefficient, switching duty ratio and carrier amplitude result in reduced conducted EMI noise shown by simulations in [9, 18] and experiments shown in [4, 19].

However, the work of [7] will add to the resistive losses due to the increment of the gate series resistance, reduces active power and increases reactive power drawn from supply at higher dc output voltages, and the added capacitive compensation and voltage boost add to the components. The method in [6] is applicable to low frequency range only. Soft switching technique presented in [10, 11] needs snubber circuits which could increase losses. The compensating transformer and capacitor in [14] will increase size and will introduce resonance between the capacitance and the inductances causing more noise especially at higher switching frequencies. The auto-tuning approach described in [8] only focuses on the internal EMC of the converter and it needs an additional board to perform the frequency scanning. The randomized modulation adopted in [4, 9, 18, 19] results in ripple of the output voltage and current which could be a source of increased EMI noise, and makes use of large output filter capacitor. The use of space vector modulation to switch at zero voltage states is problematic in the way it results in reduced CM and worst DM noise [31].

3.0 Research Activities

3.1 Self study of power electronics converters and industrial drives from online courses [42] and books [1, 33, 34].

3.2 I have done one Seminar talk on 4th January 2011. It enabled a broad discussion of the issues with the faculty at the department and other postgraduate students.

3.4 I visited the SAMEER Centre for Electromagnetics [41]. I had an opportunity to see the work done by the centre in EMI/EMC Test and seen their Design and Consultancy facility.

3.5 I have started simulation work using SABER and SIMULINK.

3.6 I have been auditing two courses namely Electromagnetic Fields and Analog and Digital Signal Processing to provide knowledge of the research problem.

4.0 Conclusion and Future Work

A case has been made that there is need to carry out investigation of reducing EMI noise in power converters. The modelling work has started by simulations using SABER and SIMULINK. It is expected to identify suitable modelling approaches for reducing EMI noise effects of power electronic converters. Also, it is expected to verify the simulation results by experimental work.

5.0 Acknowledgement

I acknowledge the Centre for International Cooperation in Science (CICS) for funding the research training. Professor Krishna Vasudevan is highly acknowledged for accepting to be my mentor during this time to carry out the training. Also, I acknowledge Professor C. S. Ramalingam and Professor Shanti Bhattacharya for allowing auditing of their courses. All members of power electronics and industrial drives group are acknowledged for helping and assisting in one way or another to make the training fruitful.

6.0 References

1. V. P. Kodali, "*Engineering Electromagnetic Compatibility: Principles, Measurements, and Computer Models*", 2nd Edition, Wiley-India Edition, 2010.
2. A. Keith and A. E. Hutley, "*Banana Skins*", available online http://www.compliance-club.com/pdf/banana%20skins.pdf, 2007.
3. J. D. Kagerbauer and T. M. Jahns, Development of an Active dv/dt Control Algorithm for Reducing Inverter Conducted EMI with Minimal Impact on Switching Losses, *IEEE Power Electronics Specialist Conference*, pp. 894 – 900, 2007.
4. H. Li, Z. Li, B. Zhang, W. K. S. Tang and W. A. Halang, Suppressing Electromagnetic Interference in Direct Current Converters, *IEEE Circuits and Systems Magazine*, *Vol. 9, No. 4*, pp. 10 – 28, 2009.
5. W. H. Parker, Electromagnetic Interference: A Tutorial, *IEEE Aerospace Applications Conf., Vol. 3*, pp. 177 – 186, Gaithersberg, MD:Aspen, Feb. 3 – 10, 1996.
6. Fardoun, A. A, Ismail, E. H, Reduction of EMI in AC Drive Through Dithering Within Limited Switching Frequency Range, *IEEE Trans. Power Electr., Vol. 24, No. 3*, pp. 804 – 811, 2009.
7. J. A. M. Bleijs, Continuous Conduction Mode Operation of Three-Phase Diode Bridge Rectifier with Constant Load Voltage, *IEE Proc. Electr. Power Appl., Vol. 152, No. 2*, pp. 359 – 368, March 2005.
8. C. Attaianese, V. Nardi and G. Tomasso, EMC of Power Converters: The Self-Compatibility Approach, *IET Electrical Power Applications, Vol. 1, No. 6*, pp. 862 – 869, 2007.

9. W. Zhou and S. Qiu, Effectiveness of Dual Chaotic Modulation to EMI Suppression in Power Converter, *2007 Int. Conf. on Machine Learning and Cybernetics, Vol. 1*, pp. 319 – 323, 2007.
10. H. Chung, S. Y. R. Hui and K. K. Tse, Reduction of Power Converter EMI Emission Using Soft-Switching Technique, *IEEE Trans. Electromag. Compat., Vol. 40, No. 3*, pp. 282 – 287, August 1998.
11. G. W. White and T. J. E. Miller, Soft-Switching in Aircraft Power Conversion Systems, *IEE Colloquium on Resonant Systems*, pp. 5/1 – 5/8, 1995.
12. X. Pei, K. Zhang, Y. Kang and J. Chen, Analytical Estimation of Common Mode Conducted EMI in PWM Inverter, *Conf. Rec. of the 2004 IEEE IAS and 39th IAS Annual Meeting, Vol. 4*, pp. 2651 – 2656, 2004.
13. K. Mainali and R. Oruganti, Conducted EMI Mitigation Techniques for Switch-Mode Power Converters: A Survey, *IEEE Trans. on Power Electronics*, *Vol. 25, No. 9*, pp. 2344 – 2356, September 2010.
14. D. Cochrane, D. Y. Chen and D. Boroyevic, Passive Cancellation of Common-Mode Noise in Power Electronic Circuits, *IEEE Trans. on Power Electronics, Vol. 18, No. 3*, pp. 756 – 763, May 2003.
15. Liu Yucheng and Liu Yubin, Design Strategy of Anti-Electromagnetic Interference for Microcomputer Relay Protection System, *2010 International Forum on Information Technology and Applications*, pp. 180 – 183, 2010.
16. X. Wenyan, C. Xiao and M. Xikui, Analysis and Reduction of Conducted EMI from an AC/DC High Power Converter, *2005 IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications Proceedings*, pp. 503 – 506, 2005.
17. American National Standard Recommended Practice for Electromagnetic Compatibility Limits, ANSI C63.12-1999.
18. S. Banerjee, D. Kastha, and S. SenGupta, Minimising EMI Problems with Chaos, *Proceedings of INCEMIC 2001 – 2002*, pp. 162-167.
19. S. Barnejee, A. L. Baranovski, J. L. R. Marrero and O. Woywode, Minimizing Electromagnetic Interference Problems with Chaos, Review Paper, *IEICE Transactions, Vol. E85-A, No. 1*, January 2002.
20. D. Jiang, R. Lai, F. Wang, F. Luo, S. Wang and D. Boroyevich, Study of Conducted EMI Reduction for Three-Phase Vienna-Type Rectifier, *The 2010 International Power Electronics Conference*, pp. 1118-1124, 2010.
21. N. F. Oswald, B. H. Stark, C. Hargis, W. Dury and D. Holliday, Synthesising Power Electronic Waveforms for Reduced EMI Generation, University of Bristol, UK.
22. A. Micalef, C. S. Staines and M. Apap, Modeling of an EMC Test-Bench for Conducted Emissions in Solid State Applications, *IEEE Transactions*, pp. 80-86, 2010.
23. A. C. Baiden, D. Boroyevich and F. W. Wang, Generalized Terminal Modelling of Electromagnetic Interference, *IEEE Transactions on Industry Applications*, *Vol. 46, No. 5*, pp. 2068-2079, September/October 2010.
24. A. J. Sinclair, J. A. Ferreira and J. D. van Wyk, A Systematic Study of EMI Reduction by Physical Converter Layout and Suppressive Circuits, *IEEE Transactions*, pp. 1059-1064, 1993.
25. E. Gaio, R. Piovan and V. Toigo, EMI on Diagnostics and Control Circuits due to Switching Power Supplies, Available online at www.sciencedirect.com, 2005.
26. B. Mesgarzdeh and A. Alvandpour, EMI Reduction by Resonant Clock Distribution Networks, *IEEE Transactions*, pp. 977-980, 2010.

27. S. Wang, Y. Y. Maillet, F. Wang, R. Lai, F. Luo and D. Boroyevich, Parasitic Effects of Grounding Paths on Common-Mode EMI Filter's Performance in Power Electronic Systems, *IEEE Transactions on Industrial Electronics*, *Vol. 57, No. 9*, pp. 3050-3059, September 2010.
28. H. Guo, Z. Li and B. Zhang, Characteristic Analysis of Switching Voltage Power Spectra under the Mode of Random Carrier-Frequency Modulation, *The International Journal For Computation and Mathematics in Electrical and Electronic Engineering*, *Vol. 29, No. 2*, pp. 484-494, 2010.
29. M. Senesky, G. Eirea and T. J. Koo, Hybrid Modelling and Control of Power Electronics, University of California.
30. A. M. de Broe, A. L. Julian and T. A. Lipo, Neutral to Ground Voltage Minimization in a PWM-Rectifier/Inverter Configuration, *Power Electronics and Variable Speed Drives Conference Publication, No. 429,* pp. 564-568, 23-25 September 1996.
31. A. Bellini, G. Francseschini, R. Rovatti, G. Setti and C. Tassoni, Generation of low-EMI PWM Patterns for Induction Motro Drives with Chaotic Maps, *IECON'01: The 27th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1527-1532, 2001.
32. G. Orti, A. L. Julian and T. A. Lipo, A New Vector Modulation Strategy fopr Common Mode Voltage Reduction, *IEEE Xplore*, pp. 1541-1546, 1997.
33. B. K. Bose, *Modern Power Electronics and AC Drives*, pp. 224-236, Prentice Hall, 2005.
34. M. H. Rashid, *Power Electronics Circuits, Devices, and Applications*, pp. 271-279 & pp. 406-429, PHI Learning Private Ltd., New Delhi-110001, 2009.
35. H. Zhang, A. von Jouanne, S. Dai, A. K. Wallace and F. Wang, Multilevel Inverter Modulation Schemes to Eliminate Common-Mode Voltages, *IEEE Transactions on Industry Applications, Vol. 36, No. 6*, pp. 1645-1653, November/December 2000.
36. Y-S. Lai and Y-T. Chang, Design and Implementation of Induction Motor Drives using Random Switching Technique, *IEEE Xplore*, pp. 2487-2492, 2000.
37. L. Ran, S. Gokani, J. Clare, K. J. Bradley and C. Christopoulos, Conducted Electromagnetic Emissions in Induction Motor Drive Systems Part II: Frequency Domain Models, *IEEE Transactions on Power Electronics, Vol. 13, No. 4*, pp. 768-776, July 1998.
38. V. Naumanen, J. Korhonen, J. Luukko and P. Silventoinen, Multilevel Inverter Modulation Method to Reduce Common-mode Voltage and Overvoltage at the Motor Terminals, *IEEE 26th Convention of Electrical and Electronics Engineers in Israel*, pp. 000296-000300, 2010.
39. L. Ran, S. Gokani, J. Clare, K. J. Bradley and C. Christopoulos, Conducted Electromagnetic Emissions in Induction Motor Drive Systems Part I: Time Domain Analysis and Identification of Dominant Modes, *IEEE Transactions on Power Electronics, Vol. 13, No. 4*, pp. 768-776, July 1998.
40. K. Muttaqi and M. E. Haque, Electromagnetic Interference Generated from Fast Switching Power Electronic Devices, *International Journal in Eneryg Systems and Power, Vol. 3, No. 1*, pp. 19-26, April 2008.
41. Society for Applied Microwave Electronics Engineering Research, online http://www.sameer.gov.in
42. National Programme on Technology Enhanced Learning, online http://nptel.iitm.ac.in/

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