International Journal of Electrical Electronics & Computer Science Engineering
Volume 2, Issue 5 (October, 2015) | E-ISSN : 2348-2273 | P-ISSN : 2454-1222
Available Online at www.ijeecse.com

Inductor Current Based Fault Diagnostic System for Four Port DC/DC Converter

T. K. Santhosh[1], C. Govindaraju[2]
[1]Ph.D. Scholar, [2]Assistant Professor
Department of Electrical & Electronics Engineering, Government College of Engineering, Salem, Tamil Nadu
[1]tksanthosh.kct@gmail.com, [2]drcgovindaraju@gmail.com

Abstract: ***Power converters are increasingly deployed in mission critical systems. A controller is deployed to regulate the output of the power converter. A classical control system regulator thrives to attain the control objective corresponding to the variation in system parameters. Such systems are not capable of handling faulty systems. Diagnosing a fault and taking a corrective action is equally important to regulating converter output. The periodic variation in the inductor current is utilised as a parameter to diagnose the fault in the system. The implementation of the fault diagnostic system and its simulation results are presented. The fault diagnostic system could be extended to any power converter with inductor operating in continuous conduction mode.***

Keywords: Fault diagnostic, Four Port Converter, DC/DC converter, Fault identification, MATLAB/Simulink.

I. INTRODUCTION

With increased utilisation of regulated power, power converters penetrated into almost every application [1]. Power converters penetrated into virtually every field that uses some form of electric energy. Some of these applications include renewable automotive [2], smart grid [3], UPS [4], medical and aerospace systems [5]. While maintaining the constant regulated voltage [6] or current [7], [8], ensuring the safety of the power converter is equally important. Any anomaly in the operation of the power converter should be diagnosed at the right time to avoid a capital loss of sources of energy and switching devices. The process of fault detection, identification and remedial action is termed as a fault-tolerant strategy [9]. More than 50% of failures and breakdowns are due to electrolytic capacitor failures, and 30% of fails are due to power semiconductor devices [10]. Fault diagnostic system has been embracing several topologies of inverters [11] and dc–dc converters [9], [12]–[15]. A survey was conducted to understand the reliability expectations and requirements of power converters [16]. The survey reports that semiconductor switches are the most fragile components and are prone to frequent failures. The type of fault could be a Short Circuit Fault (SCF) or an Open Circuit Fault (OCF). Both faults could cause fatal damages to the power converter and its associated end equipment. The damages could be avoided if the if the fault is properly diagnosed. Monitoring of the converter parameters [17] is a popular choice to identify faults. Persistence of faults could lead to the failure of healthy switches, inductors and even power resources. The presence of faults shall have a direct impact on the periodicity of the inductor current.

As the inductor forms the front end of the power converter, a fault inside the power converter will be reflected in the inductor current. The originality of the work lies in the utilisation of the periodicity of inductor current for fault diagnosis. The general form of fault diagnosis is developed for Hybrid Electric Vehicle (HEV) applications. The developed algorithm is verified by testing it on a Four Port converter developed for HEV applications.

II. GENERIC STRUCTURE FOR FAULT DIAGNOSIS

Fault diagnosis is necessary to protect the converter system and sources from fatal damage. Identification of faults at the instant of occurrence and isolating the converter could be available step compared to converter system failure. Normal operation translates to periodic charging and discharging cycle in inductor current. The charging and discharging slopes [18] occur at a time interval equal to the switching period. During fault conditions, this regular cycle is disturbed.

A. Fault Diagnostic Algorithm

The fault diagnostic system has to perform a series of steps before a fault is declared. The steps are listed as follows:

- The inductor current is sampled at a particular time instant.
- Then the inductor current is sampled at one-fourth time from the previous sampling.
- Based on the two values, this slope is calculated and its sign is determined.
- The above three steps are repeated for the upcoming switching cycle.
- If the values of two computed slopes are the same, the converter is healthy.
- If not, a fault is declared and the type of fault is notified based on the variation in slope.
- If the slope is continuously falling, it could be categorised as an open circuit fault. Similarly, rising slope corresponds to short circuit fault.

International Journal of Electrical Electronics & Computer Science Engineering
Volume 2, Issue 5 (October, 2015) | E-ISSN : 2348-2273 | P-ISSN : 2454-1222
Available Online at www.ijeecse.com

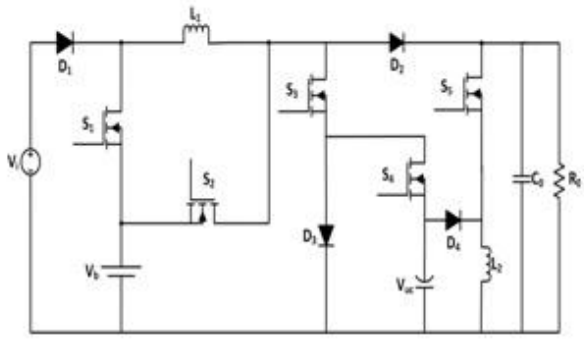

Figure 1. Four Port MIC Topology for HEV [20]

The fault diagnostic system shall observe the inductor current continuously all along the working of the power converter. Once the fault is detected, reset signal will be sent to the control system. In mission critical systems, fault identification and isolation will be a lot more helpful than supplying an unregulated power to the critical loads.

III. CASE STUDY

A. *Converter Topology*

A To test the feasibility of the inductor current based control and fault detection, a Four Port Converter(FPC) proposed for Hybrid electric vehicle [19], [20] is chosen. The power circuit of the FPC selected for the implementation of fault diagnostic algorithm is shown in Fig. 1.

While the converter possesses six different operating modes, a mode selection logic is employed to handle mode selection. The FPC has a closed loop control algorithm to regulate output voltage [8]. The converter has two inductors named L_1 and L_2. A typical inductor waveform is shown in Fig. 2. Each mode has two switching states. During the first state of the first five operating modes, the inductor charges to a certain level. The second switching state shall be utilised to deliver the inductor stored energy to the load. The first five operating modes show the behaviour of a boost converter. The sixth operating modes correspond to regeneration. The regenerated voltage has to be stepped down and polarity inverted to be able to store it in the ultracapacitor. Mode VI works in a way similar to the buck-boost behaviour. In all these modes, one could observe a periodic variation of the inductor current. The exact magnitude of inductor current could be found in Table I. The charging slope is denoted by a variable (A*) and the discharging slope is denoted by the variable (B*). The devised algorithm is tested for a particular mode using inductor current. This converter is selected to ensure the fact that the generic structure of fault detection based on inductor current applies to any converter system as long as the inductor current process periodicity. The inductor current of the converter in different operating modes is listed in Table I.

B. *Implementation of Fault Diagnosis Algorithm*

The algorithm developed for inductor current based fault detection has to be implemented in a digital controller. The fault diagnostic system is completely modelled with MATLAB/Simulink. The schematic used for interpretation of slopes and fault diagnosis is shown in Fig.3.

Table I. Summary of Different Operating Modes

Operating Mode	Conducting Switches		Inductor Current	
	State I	State II	Charging Slope $(A*)$	Discharging Slope $(\boldsymbol{B*})$
Mode 1	S_3, D_1, D_3	D_1, D_2	$\frac{V_i}{L_1}$	$\frac{V_i - V_o}{L_1}$
Mode 2	S_1, S_3, D_3	S_1, D_2	$\frac{V_b}{L_1}$	$\frac{V_b - V_o}{L_1}$
Mode 3	S_3, S_4, D_1	D_1, D_2	$\frac{V_i + V_{uc}}{L_1}$	$\frac{V_i - V_o}{L_1}$
Mode 4	S_1, S_3, S_4	S_1, D_2	$\frac{V_b + V_{uc}}{L_1}$	$\frac{V_b - V_o}{L_1}$
Mode 5	S_3, D_1, D_3	S_2, D_1	$\frac{V_i}{L_1}$	$\frac{V_i - V_b}{L_1}$
Mode 6	S_5	D_4	$\frac{V_o}{L_2}$	$\frac{V_{uc}}{L_2}$

International Journal of Electrical Electronics & Computer Science Engineering
Volume 2, Issue 5 (October, 2015) | E-ISSN : 2348-2273 | P-ISSN : 2454-1222
Available Online at www.ijeecse.com

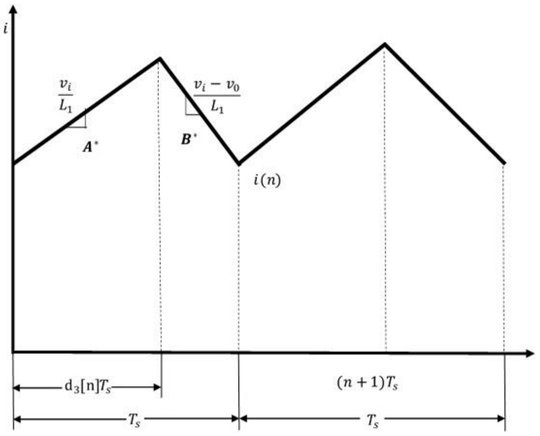

Fig. 2. Periodic Variation in the Inductor Current Waveform

The slope calculation forms the main part of the algorithm. At each switching cycle, the inductor current is sampled at two time instants and the corresponding slopes are calculated. The difference in the magnitude of the slopes is first computed. Then the difference in time is computed and the magnitude difference is divided by the time difference to obtain the slope. One two such samplings are calculated, the comparison between these two slopes are done. A normal operation would return same slopes and the system is declared healthy. In the case of abnormal conditions, the slopes would have different values and the system is declared faulty. In the event of a faulty power converter, the type of the fault could be identified by inspecting the variation in slope. A continuous increase in the slopes would correspond to the short circuit characteristic and a Short Circuit Fault (SCF) is declared. Once an Open Circuit Fault (OCF) happens, the switching action does not have any impact on the inductor current. The inductor current shall drop steeply on the occurrence of a fault and then the small constant current shall flow to the load. Due to the absence of current variations, the inductor shall act as a mere resistance. An OCF fault is declared in such drooping inductor current case.

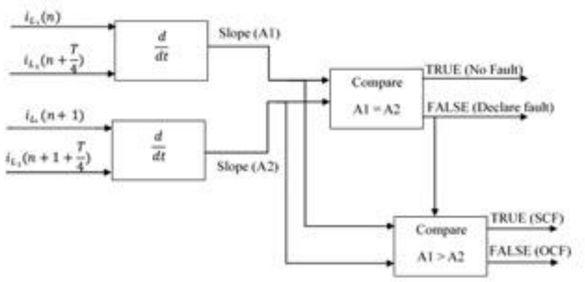

Fig. 3. Block Diagram for Implementation of Fault Diagnostic System

The fault diagnostic system is tested with two types of faults. An open circuit fault is generated by placing an ON/OFF switch in series with the switching device and opening it when the fault has to be created as shown in Fig.4. An SCF is created by placing an ON/OFF switch in parallel with the switching device. When this ON/OFF switch is closed, a short is applied across the switch which emulates the short circuit as shown in Fig. 5. The fault diagnosis system is monitoring the inductor current by sampling it at appropriate time instants.

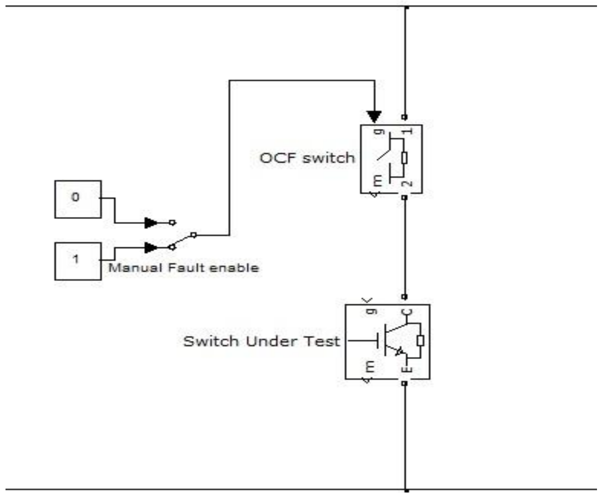

Fig. 4. Test Arrangement for Manual OCF Generation

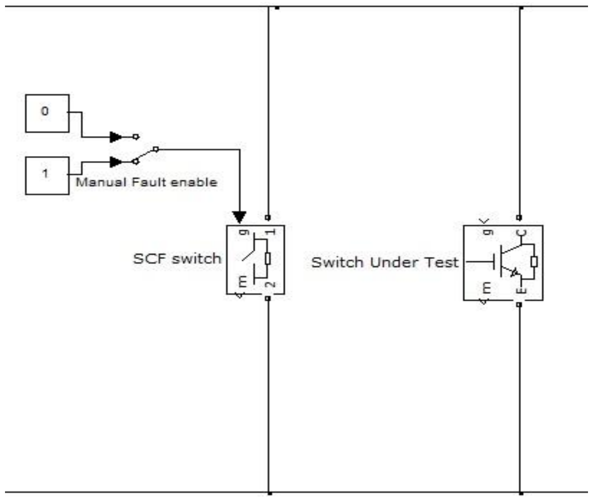

Fig. 5. Test Arrangement for Manual SCF Generation

IV. RESULTS AND DISCUSSION

When an OCF is created manually, the slope of inductor current will fall suddenly to a lower magnitude as shown in Fig. 6. The fault diagnostic system will declare the occurrence of a fault and also notify the type of fault. The SCF is generated by closing the SCF switch. A short circuit will lead to the sudden rise in current as shown in Fig. 7. In other words, the slope if the inductor current will be rising as shown in Fig.7. The rising inductor current would result in an increase in the magnitude of slopes. Within few switching cycles after the fault is forced to occur, the fault diagnostic system captures the anomaly in inductor current and declare the fault occurrence. The fault diagnostic system could be made accurate if the operating ranges of the inductor current are known.

International Journal of Electrical Electronics & Computer Science Engineering
Volume 2, Issue 5 (October, 2015) | E-ISSN : 2348-2273 | P-ISSN : 2454-1222
Available Online at www.ijeecse.com

While the proposed fault diagnostic system works well, it is also possible that the system could misinterpret a sudden variation in load as a fault case scenario. A sudden variation in load would lead to an inductor current scenario similar to the fault case. The fundamental difference between the fault and load variation is the time period. While the changes forced by load variations are intermittent, the effect of fault shall have a long lasting impact. The diagnostic could be improved if the system repeats its process for at least four switching cycles before fault declaration. The extended period of observance could be helpful in diagnosing a fault rather than a sudden variation in load. This work could be extended to any type of isolated or non-isolated versions of power converters.

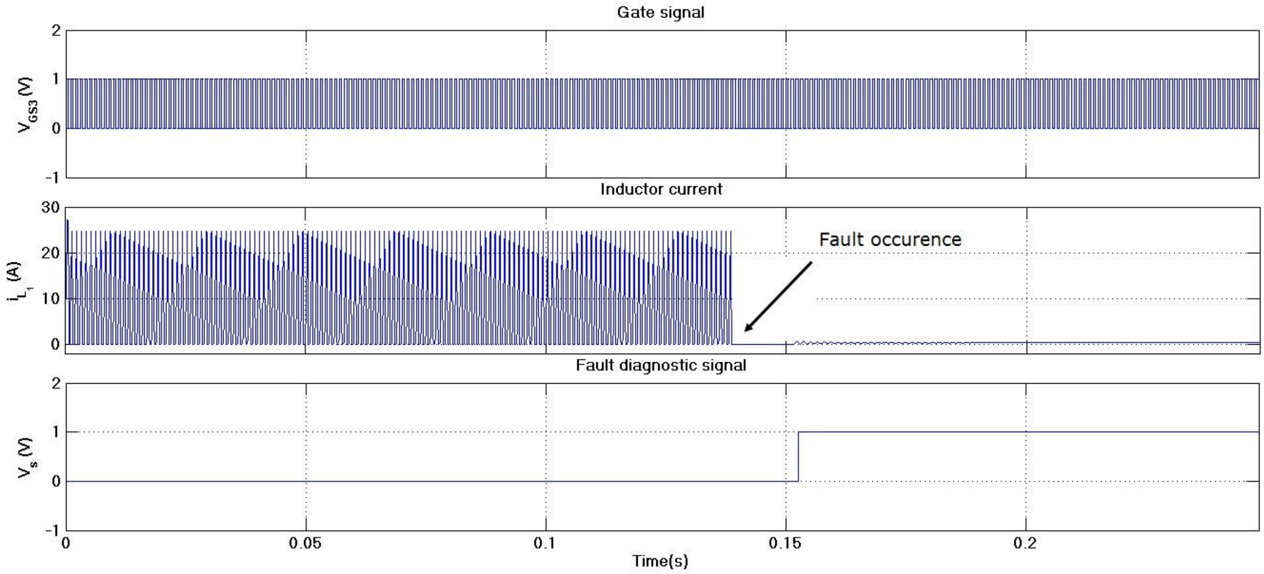

Fig. 6. Open Circuit Fault & Its Diagnosis

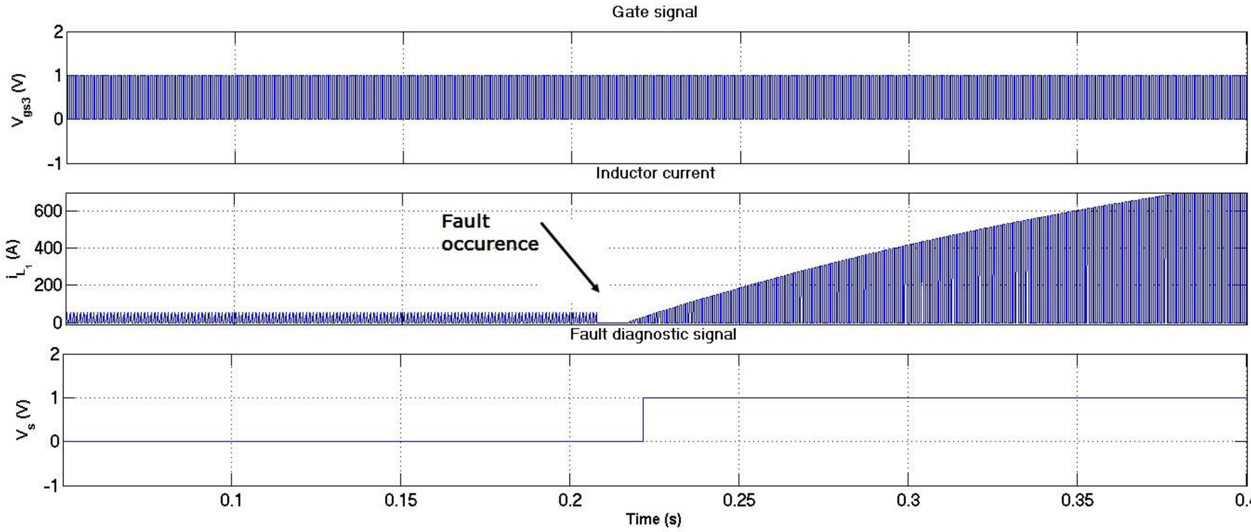

Fig. 7. Short Circuit Fault & Its Diagnosis

V. CONCLUSIONS

This work proposes a generic structure of inductor current based fault detection applicable to any power converter operating in continuous conduction mode. A power converter operating in a normal condition has a switching device which leads to a periodic variation in inductor current. The fault diagnostic is based on the fact that if there is a fault in the converter, the periodicity is disturbed. A close monitoring of the inductor current could reveal the operating status of the converter. The fault diagnostic system proposed in this work is capable of fault detection and isolation. The proposed system is applied to an FPC developed for HEV applications. Two types of fault namely, OCF and SCF are manually created and the system response is observed. The fault diagnostic system is capable of identifying faults within few switching cycles of its occurrence. While the proposed system works for FPC, it could be extended to any converter whose inductor current shows a periodic variation.

VI. REFERENCES

[1] B. K. Bose, “Global Energy Scenario and Impact of Power Electronics in 21st Century,” IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2638–2651, Jul. 2013.

[2] T. Zhang, W. Chen, Z. Han, and Z. Cao, “Charging scheduling of electric vehicles with local renewable energy under uncertain electric vehicle arrival and grid power price,” IEEE Trans. Veh. Technol., vol. 63, no. 6, pp. 2600–2612, 2014.

[3] D. P. Tuttle and R. Baldick, “The Evolution of Plug-In Electric Vehicle-Grid Interactions,” IEEE Trans. Smart Grid, vol. 3, no. 1, pp. 500–505, Mar. 2012.

[4] B.-Y. Y. Chen and Y.-S. S. Lai, “New digital-controlled technique for battery charger with constant current and voltage control without current feedback,” IEEE Trans. Ind. Electron., vol. 59, no. 3, pp. 1545–1553, Mar. 2012.

[5] R. Erickson and D. Maksimovic, Fundamentals of Power Electronics (Second Edition). Springer, 2001.

[6] H. Wu, C. Wan, K. Sun, and Y. Xing, “A High Step-Down Multiple Output Converter With Wide Input Voltage Range Based on Quasi Two-Stage Architecture and Dual-Output LLC Resonant Converter,” IEEE Trans. Power Electron., vol. 30, no. 4, pp. 1793–1796, 2015.

[7] T. K. Santhosh and C. Govindaraju, “Development of Predictive Current Controller for Multi-Port DC/DC Converter,” Int. J. Power Electron. Drive Syst., vol. 6, no. 4, Dec. 2015.

[8] T. K. Santhosh and C. Govindaraju, “Stability Analysis and Control Design of a Four Port DC/DC Converter,” Journal of Electrical Engineering and Power Electronics, vol. 1, no. 1. pp. 8–18, 01-Dec-2015.

[9] R. L. de Araujo Ribeiro, C. B. Jacobina, E. R. Cabral da Silva, and A. M. Nogueira Lima, “Fault detection of open-switch damage in voltage-fed PWM motor drive systems,” IEEE Trans. Power Electron., vol. 18, no. 2, pp. 587–593, Mar. 2003.

[10] A. M. R. Amaral and A. J. M. Cardoso, “On-line fault detection of aluminium electrolytic capacitors, in step-down DC–DC converters, using input current and output voltage ripple,” IET Power Electron., vol. 5, no. 3, pp. 315–322, Mar. 2012.

[11] N. M. A. Freire, J. O. Estima, and A. J. Marques Cardoso, “Open-Circuit Fault Diagnosis in PMSG Drives for Wind Turbine Applications,” IEEE Trans. Ind. Electron., vol. 60, no. 9, pp. 3957–3967, Sep. 2013.

[12] A. Mohammadi, D. Guilbert, A. Gaillard, D. Bouquain, D. Khaburi, and A. Djerdir, “Faults diagnosis between PEM fuel cell and DC/DC converter using neural networks for automotive applications,” in IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, 2013, pp. 8186–8191.

[13] B. Akin, S. B. S. B. Ozturk, H. a. H. A. Toliyat, and M. Rayner, “DSP-Based Sensorless Electric Motor Fault Diagnosis Tools for Electric and Hybrid Electric Vehicle Powertrain Applications,” IEEE Trans. Veh. Technol., vol. 58, no. 5, pp. 2150–2159, 2009.

[14] E. Ribeiro, A. J. M. Cardoso, and C. Boccaletti, “Fault-Tolerant Strategy for a Photovoltaic DC--DC Converter,” IEEE Trans. Power Electron., vol. 28, no. 6, pp. 3008–3018, Jun. 2013.

[15] E. Ribeiro, S. Member, A. J. M. Cardoso, S. Member, and C. Boccaletti, “Open-Circuit Fault Diagnosis in Interleaved DC–DC Converters,” IEEE Trans. Power Electron., vol. 29, no. 6, pp. 3091–3102, 2014.

[16] S. K. Sharma, “A Literature Review of IGBT Fault Diagnostic and Protection Methods for Power Inverters,” IEEE Trans. Ind. Appl., vol. 45, no. 5, pp. 1770–1777, 2009.

[17] R. Jayabalan and B. Fahimi, “Monitoring and fault diagnosis of DC-DC multistage converter for hybrid electric vehicles,” in 2005 5th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, 2005, pp. 1–6.

[18] P. T. Krein, J. Bentsman, R. M.Bass, and B. L.Lesieutre, “On the Use of Averaging for the Analysis of Power Electronic Systems,” IEEE Trans. Power Electron., vol. 5, no. 2, pp. 182–190, 1990.

[19] T. K. Santhosh and C. Govindaraju, “Simulation and Analysis of a Four Port DC / DC Converter for Hybrid Electric Vehicle,” in International Conference on Power and Energy Systems: Towards Sustainable Energy(PESTSE 2014), 2014, pp. 236–240.

[20] T. K. Santhosh, K. Natarajan, and C. Govindaraju, “Synthesis and Implementation of Multi-Port DC/DC Converter for Hybrid Electric Vehicle,” J. Power Electron., vol. 15, no. 5, pp. 1178–1189, 2015.

Authors

T. K. Santhosh received his B.E degree in Electrical and Electronics Engineering from Kumaraguru College of

Technology, Coimbatore, India in 2009 and M.E degree in Power Electronics and Drives from K.S.R.College of Engineering, Tiruchengode, India in 2011. He is currently working toward his Ph.D. in Electrical Engineering at Government College of Engineering, Salem under Anna University, Chennai. His research interest includes multiple input converters for an electric vehicle, digital control of power electronic systems and renewable energy.

Dr. C. Govindaraju received his B.E degree in Electrical and Electronics Engineering from Government College of Engineering, Salem, in 1999 and M.E. degree in Power Electronics and Drives from College of Engineering, Anna University, Chennai, in 2003. He received Ph.D. in the field of energy efficient multilevel inverters in Anna University, Chennai in 2011. He is an Assistant Professor in the department of Electrical and Electronics Engineering, Government College of Engineering, Salem, Tamilnadu, India. His research interest includes multilevel inverters, power electronics interface for renewable energy systems, and Smart grids.